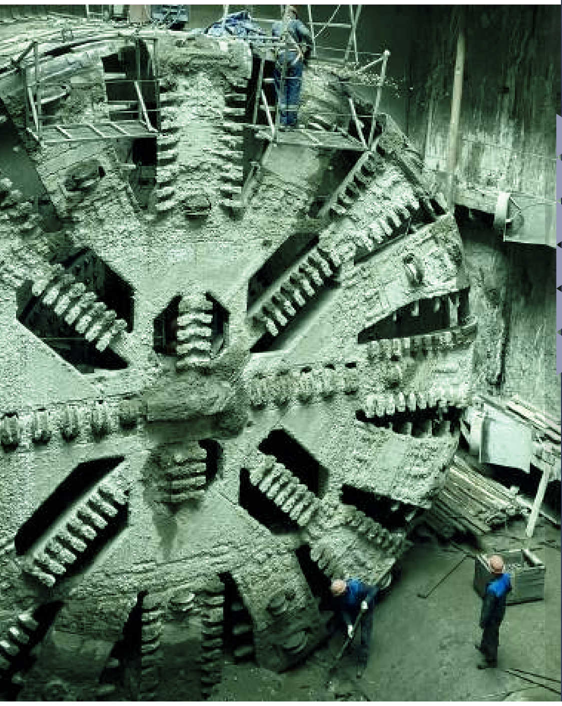
South African National Committee on Tunnelling

SANCOT SYMPOSIUM 2026

13-14 APRIL 2026
SOUTHERN SUN ROSEBANK,
JOHANNESBURG



Unlocking Africa's Potential: Advances in Tunnelling in Civil Engineering and Mining

Proceedings Book

SAIMM
THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

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Unlocking Africa's Potential: Advances in Tunnelling in Civil Engineering and Mining

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FOREWORD

From the Chairperson of the Organising Committee of SANCOT Symposium 2026

It is with great pleasure that I present to you these proceedings of SANCOT Symposium 2026 held in Rosebank, Johannesburg, Gauteng, South Africa.

Rosebank, situated in the heart of Johannesburg's northern suburbs, is one of the city's most vibrant commercial and cultural hubs. Known for its modern office parks, bustling shopping centres, excellent restaurants, thriving arts scene at venues like the Everard Read Gallery, and the popular Rosebank Sunday Market, this cosmopolitan precinct embodies Johannesburg's transformation into a world-class African city. The area's central location provides easy access to Johannesburg's rich heritage sites, including the Apartheid Museum, Constitution Hill, and nearby Soweto, as well as the natural beauty of the Walter Sisulu Botanical Gardens. We sincerely hope that while here you will enjoy the city's renowned hospitality, diverse culinary offerings, vibrant cultural experiences, and dynamic urban energy.

We chose the theme **'Unlocking Africa's Potential: Advances in Tunnelling in Civil Engineering and Mining'** for SANCOT Symposium 2026 to showcase the continent's growing capacity in underground construction and to highlight the critical role that tunnelling plays in Africa's infrastructure development and mineral resource extraction. With several major civil engineering water transfer and transport projects underway alongside innovative mining developments incorporating cutting-edge technology across Southern Africa, the region presents a compelling narrative of technical advancement and economic growth through tunnelling, including:

- **Polihali Transfer Tunnel,** part of Phase II of the Lesotho Highlands Water Project (LHWP P2).
- Advanced mining decline and shaft development at various deep-level gold and platinum mines in South Africa, incorporating latest technology and safety innovations.
- **uMkhomazi Water Project Phase I (uMWP-1)**, a proposed water tunnel in KwaZulu Natal.
- **Oxbow Hydropower Project**, proposed hydropower tunnels and caverns in Lesotho.
- **Gautrain expansion projects,** including proposed extensions to Cosmo City, Soweto and Mamelodi, requiring extensive tunnel works in Johannesburg and Pretoria

We are also delighted to feature keynote presentations from several international experts covering topics such as geotechnical baseline reports, productivity challenges in tunnelling, and the synergies between mining and civil engineering practices. The technical programme encompasses geotechnical risk management (including new DMPR guidelines), mechanised boring technologies, pressure tunnel design, ground support systems, and digital data capture for tunnel construction. Several papers and presentations included in these proceedings provide comprehensive updates on major regional projects including the uMWP-1 and LHWP P2. The symposium also addresses the application of mechanised boring in mining, innovative shaft sinking technologies for deep mining operations, and logistical challenges in long-distance tunnelling, all critical to the region's infrastructure and resource development. Participation by the International Tunnelling and Underground Space Association further connects African practitioners with global tunnelling knowledge and best practices. The symposium proceedings thus reflect extensive local, regional, and international experience in tunnelling and underground construction, and we trust it will prove to be a valuable resource for tunnelling projects throughout Southern Africa and beyond.

Finally, we hope that all delegates attending the symposium here in Rosebank will leave with good memories of another successful SANCOT symposium where new acquaintances were made and old friendships renewed while sharing information on emerging tunnelling technologies, discussing progress on various projects, learning from both successes and challenges, and building collaborative networks that will advance the tunnelling profession across our continent.

Best wishes as always.
R. Freese,
Chairperson: Organising Committee

Contents

Page No

The organisers of the conference thanks the following sponsors for their support

ASM Winzing applied in an East African gold mine

S.M. Rupprecht, L.A. Langton

University of Johannesburg, South Africa

This paper presents a case study of the winze development at a gold mining project in East Africa, offering practical insights into tunnelling methods tailored for artisanal and small-scale mining (ASM) operations. Drawing from firsthand experience, the study documents the complete mining cycle—including drilling, blasting, mucking, and ground support—implemented in a constrained underground environment.

Two distinct blast designs are analysed, with specifications on drill hole diameters, drill steel, explosive types, and achieved advance per round. The paper also outlines the modified rock removal method adopted to accommodate the mine's logistical limitations, as well as the support systems used to stabilize ground conditions. Cycle times for each activity are provided to illustrate operational efficiency and to benchmark performance in similar small-scale contexts.

The study highlights the practical challenges encountered during development—ranging from equipment limitations and ground control issues to logistical constraints—and critically examines the solutions applied. Emphasis is placed on the adaptability and ingenuity required in ASM environments, where resource constraints often demand unconventional yet effective approaches.

The paper concludes with a candid assessment of what worked, what didn't, and the lessons learned. These reflections are intended to support knowledge transfer within the African mining industry and to promote safer, more productive underground development practices in ASM operations. By documenting both the technical details and the decision-making processes behind the winze development, this work contributes to the growing body of knowledge aimed at professionalising and optimising ASM tunnelling practices across Africa.

INTRODUCTION

The African continent holds immense mineral wealth, yet global sentiment and empirical data often frame it as a high-risk investment destination. Post-colonial regimes and leadership challenges have negatively influenced key modifying factors such as security of tenure, taxation policies, enabling infrastructure (roads, water, and electricity), and widespread corruption within newly established governments. These conditions create an environment in which corporate mining companies are reluctant to commit large sums to exploration and to develop mineral resources. The risk of wasting capital in efforts to establish geological data under such uncertainty has constrained the continent's ability to fully realise its mineral potential.

Against this backdrop, artisanal small-scale mining (ASM) offers a viable pathway to unlock Africa's resources in a more sustainable, incremental manner. By building a significant body of knowledge and showcasing successful case studies, mining engineers and associated professionals can help the industry adopt small-scale development methods.

This approach supported by appropriate equipment, offers a lower-risk entry point into mineral resource development. Demonstrating the effectiveness of ASM tunnelling contributes to broader socio-economic benefits, including increased employment opportunities and partial poverty reduction. The true growth and potential of Africa's mining sector can be realised when ASM methods are recognised as a credible and effective exploration and development strategy.

BACKGROUND TO ASM

Global growth of ASM

ASM has expanded significantly since the 1990s, driven by rising international demand for gold and critical minerals. The World Bank estimates that ASM now directly employs 45 million people across 80 countries, with an additional 270 million livelihoods indirectly supported (World Bank, 2025). ASM's share of global gold production has grown from 4% in the 1990s to 20% today, while its contribution to tantalum and tin stands at approximately 25% of global supply (World Bank, 2025). This growth has occurred largely outside formal regulation, creating both opportunities and risks for miners and communities.

African context and historical exclusion

In Africa, ASM is deeply rooted in colonial and apartheid legacies. Mining legislation historically excluded indigenous populations from professional careers and ownership, reinforcing poverty and marginalisation (MQA, 2025). Even after independence and the end of apartheid in 1994, many historically disadvantaged South Africans lacked access to tertiary education and professional credentials, leaving ASM as one of the few viable economic activities. Scholars argue that this exclusion created a structural dependency on ASM as a survival strategy, while large-scale mining remained dominated by multinational corporations (SciELO, 2024).

Regulatory and legal frameworks

The regulatory environment for ASM remains fragmented. In South Africa, the Mine Health and Safety Act provides a framework for occupational health and safety standards, but small-scale miners often struggle to comply due to limited resources (MQA, 2025). At the continental level, further efforts have been undertaken; for example, initiatives such as the Africa Mining Vision (2009) and the Mosi oa Tunya Declaration (2018) sought to integrate ASM into national development strategies. Despite these efforts, implementation has been uneven. Many governments remain reluctant to formalise ASM due to concerns about environmental impacts and informal trade networks (World Bank, 2025).

Technical and managerial challenges

ASM tunnelling methods are typically characterised by timbered shafts, decline ramps, and handheld drilling and blasting. These techniques, while effective under resource constraints, pose significant safety risks if not properly managed. Studies highlight the need for improved ventilation, ground support, and training to reduce accidents and enhance productivity (MQA, 2025). The lack of technical documentation on underground ASM practices represents a major gap in the literature, underscoring the importance of case studies that capture operational lessons from the field.

Opportunities for professionalisation

Recent industry briefings emphasise the potential for ASM to contribute to sustainable development if properly supported. The World Bank (2025) calls for a renewed approach based on legitimacy and professionalisation, including responsive regulatory frameworks, financial inclusion, and capacity building. Scholars argue that integrating ASM into formal economies could expand access to credit, improve safety standards, and enhance recognition of miners as legitimate stakeholders in the global minerals sector.

Global mineral demand and ASM viability

Global mineral demand has surged in 2025, making ASM-based mineral trading a viable livelihood option for Africa's poor. Rising demand for gold, cobalt, lithium, copper, and rare earths has reshaped supply chains, with ASM filling critical gaps.

ASM WINZING

Introduction

This paper adopts a case-based approach, focusing on tunnelling practices at an East African gold mining company. The methodology is designed to capture operational lessons from a shallow, small-scale underground mining operation.

The East African gold mining company operates in a region with significant geological potential but limited formal exploration investment. Here, small-scale mining via winzing offers an effective way to access deposits while reducing initial capital outlay.

The specific mineral deposit was discovered by artisanal miners known as "Kuffaris". The artisanal miners discovered significant amounts of gold in rivers and in ancient riverbeds, known as "placer deposits". These ASMs operated through hand-dug excavations and, in some cases, were supported by diesel-powered pumps.

The area in East Africa is an altered igneous complex that was volcanically active many millions of years ago. This igneous complex or volcanic area was intruded many times by hot, mineralised water containing dissolved gold, silver, and tungsten. There were dykes and sills that intruded into the area as well, but not all of these intrusive features reached the surface and were often stopped by the Gabbro hanging wall. The host rock was metamorphosed by later repetitive volcanic activity, and the ground was intruded by orogenic intrusive liquids that intruded along weak areas such as contact bedding planes (Gabbro and Pyroxenite). Within the host rock, complex geological features intersecting each other. The gold was precipitated out and mineralised along the geological structures.

Exploration target areas were identified by the East African mining company through the ASM activities of the Kuffaris located within a concession area. The exploration programme identified a gold deposit 30m wide, which dipped between 45 to 60 degrees with open-ended mineralisation at depth. A JORC compliant mineral resource was estimated and a scoping study conducted to determine the mining method and production profile. The deposit was planned to be accessed via an inclined shaft; however, early on, it was decided to sink two winzes at 45 degrees to provide early access to the deposit.

Drill and Blast

The winze is based on a single blast per day meaning that the complete development cycle of drilling, blasting, cleaning, and supporting is completed over a 24-hour period (i.e. in two shifts). The reason for the above mining cycle is because pneumatic rock drills will be used along with manual (hand) loading of broken rock. The depth of the development round (depth of pull) being influenced by the cleaning rate.

The two most common types of cuts employed in inclined development ends are burn cuts and V-cuts (wedge cut). For this project, a 5-hole burn cut was selected.

Burn cuts usually provide maximum round advance. The advantages of burn cuts are:

- The depth of the round is not dependent on the working space available for drilling holes at an angle.
- The burn cut allows for a deep pull even in tough rock formations.
- It is relatively simple to drill because all holes are parallel.
- There is generally less throw with better fragmentation.
- The resultant muck pile is higher, so it provides a better platform for scaling and bolting work.
- Round length may be shortened or lengthened without any difficulty.

Principal disadvantages of a burn cut are:

- Drilling and explosives requirements (powder factor) are higher.
- Drilling must be accurate, or results will be unfavourable.

A blasthole diameter of 45mm was chosen to promote good fragmentation. A cartridge diameter of 38mm is recommended for a 45mm blasthole diameter.

The winze development end was drilled utilising a 19 blast holes (Figure 1). The blast holes were charged with three 38mm diameter emulsion cartridges and initiated using a shock tube system, which also controlled the timing of the round by determining which blast hole is ignited first i.e., the five-hole cut was ignited first followed by the easer holes and side holes.

Winze development was carried out using pneumatic rock drills utilising a 1.2m drill steel length to provide a 0.9m advance (Table I). Pneumatic rock drills are commonly used in small-scale mining as it requires a low level of skill to operate and maintain the rock drills and associated equipment.

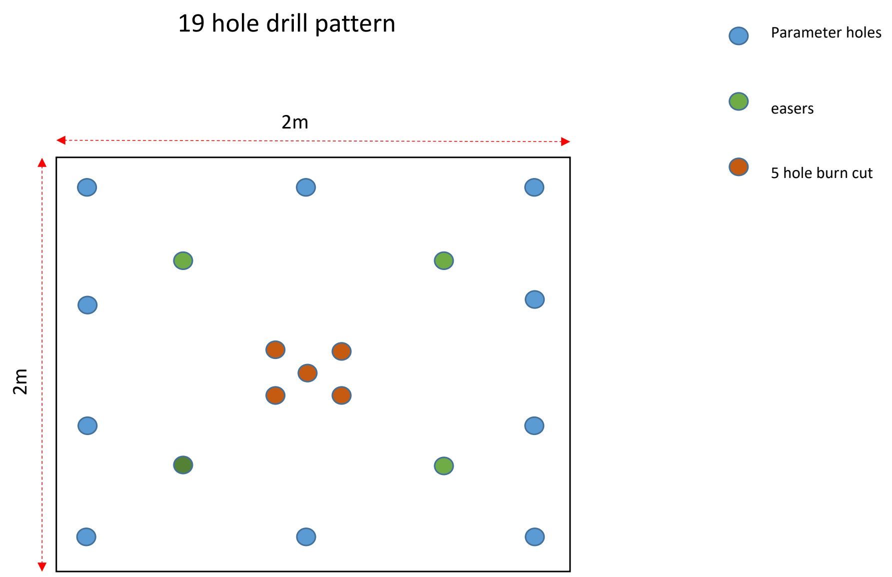

Figure 1: a) Winze marked off (NB: bottom holes below water line); b) proposed pattern

Table 1: Required time to drill face

Description	**Unit**	**Pneumatic**	**Comment**
Total holes per end	#	19	
Depth of blasthole	m	1.2	
Drill metres	m	22.8	
*Penetration Rate	m/min	0.26	4min/m
Move and reposition	min	1.5	1.0 to 1.5
Drill time	min	91.2	
Move Time	min	28.5	
Total Time	min	119.7	
Number of machines drilling	#	1	
Time to drill end	min	119.7	
Efficiency factor	%	83	
Total time per end	min	144.2	
Total Time per face	**hours**	**2.4**	

Blasting operations were conducted utilising EMEX 70 cartridge explosives, shock tube nonelectric delay initiators and 10g detonator cord.

Support
The installation of the 1.2m split sets in the winze was installed in a 2:1 diamond pattern (Figure 2). Following each round (0.9m) of excavation and barring, split sets are installed systematically in the hanging walls to ensure immediate ground stabilization. Each split set is driven fully into the hole using a pneumatic installation tool until the plate is firmly seated against the rock surface, providing active frictional support.

Figure 2: Example of Split Set Installation in Winze

Rock removal from underground to surface
A 37kW double drum scraper winch with a modified 1-tonne scraper scoop was used for cleaning Initially, it was planned to use two scraper scoops in tandem at the planned grade of 45 degrees below the horizontal. However, at this steep gradient and the uneven nature of the winze footwall the scraper scoops (buckets) were unable to maintain a reasonable fill factor, with most of the rock being lost as the scoops travelled up the winzes. The scraper scoop was then modified into a bucket (Figure) to ensure broken rock wasn't lost while pulling the scoop up the winze to the tipping point. The scraper scoop was modified by applying 10mm thick sheet metal to close the bottom and top sections of the scoop, leaving an opening of 40cm x 100cm on the top portion to allow for hand lashing into the bucket.

No signalling device was used. Instead, once the scraper bucket was full all employees travelled out of the winze before the winch operator was given permission to pull the scoop bucket up the winze.

Tipping was done by removing the shackle from the front of the bucket and attaching it to the back of the bucket. The overhead gantry directly in front of the winch allowed the winch operator to overturn the bucket and shake the rock out of the bucket. Once the bucket was emptied, the shackle would be reconnected to the front of the bucket and then the bucket would be sent back underground for loading at the winze face.

Figure 3: (a) normal scraper scoop (b) modified scraper scoop into a bucket

Cleaning efficiency

The capacity of the scoop bucket was 0.4m^3. The in-situ density of the development rock was 2.75 t/m^3 with a loose density at 1.8t/m^3. Thus, one full bucket equated to 0.72t. Total tonnage of produced per blast based on a 0.9m advance is 8.91t, which requires 13 buckets to be scraped to surface to get all the blasted rock out to surface.

The average time to load a scoop bucket, from the moment the bucket was lowered from surface to the bottom of the winze and accounting for loading using shovels, retreat of the cleaning crew to surface and for that bucket to get to surface and be tipped empty was 30 minutes. Thus, the total time to completely clean a winze blast was 390 minutes (6.5 hours). A further 30minutes of the cleaning shift was allocated to rigging activities and 60 minutes for re-entry examination and making safe. Typically, a total of eight hours was required to clean the winze which is under the 10 hour shift allotted for cleaning activities.

The cleaning system consisted of

- 37kW electrical double drum scraper winch.
- 19mm scraper rope used for with drums to standardise our material list.
- 200mm return snatch block.
- 100mm elevating snatch blocks to elevate and prevent tangling of the ropes over the pull distance.
- Sling eyebolts and pins to secure the return position.
- 16mm rigger chains to keep the 200mm return snatch block in position.
- Pig tail eyebolt for a traveling way chain.
- 1 inch air whistle.
- 12.5 mm air hose to connect the air whistle.
- 10mm bell wire with 100mm elevating snatch blocks to elevate the bell wire and prevent it from being touching the uneven footwall.

The height of the winze accommodated for the ventilation column as well as the drilling and installation of 1.8m long 39mm diameter split sets for hangingwall support.

The maximum pull distance of the scraper winch was 80m, with the limit of the pull distance based on the capacity of the scraper winch drum to store the 19mm scraper rope.

Infrastructure requirements for winzing

Electrical power

Due to the remote location of the mining site, there was no electrical infrastructure available. To support mining operations, an Atlas Copco Q380 diesel powered generator was purchased. The operational parameters of the generator are shown in Table I.

During the period of development the generator worked extremely well with a high availability and utilisation.

Table I. Operational parameters of generator

Description	
Prime power (PRP)	380kVA/304kW
Standby power (ESP)	414kVA/331kW
Rated Voltage	400V
Rated frequency	50Hz
Rated current (PRP)	548.4A
Power factor	80%

Compressed air system to power pneumatic equipment

The mine chose to purchase two units from Atlas Copco. The XATS 1200 cfm diesel-powered oil-injection rotary screw air compressor was selected. This machine was specifically designed for use with pneumatic rock drills and abrasive sand blasting. The mine used compressors to provide compressed air to pneumatic rock drills and pneumatic air pumps. Two units were chosen to ensure reliability and enable 24-hour development operation. To ensure the compressors weren't overused, compressor No. 1 was used during the day shift and compressor No. 2 during the night shift.

The XATS 1200 features a highly effective computer system that provided safeguards so that the compressor and its engine would not be damage or suffer major breakdowns. If system warnings are ignored, the machine would shut down to protect components. Although the compressors were very reliable, the operating and maintenance parameters were not well understood. Procuring spares was an initial issue with both machines, and safeguards eventually recommended halting compressor use. This occurred twice before the mine began proactively purchasing and maintaining critical spares. Reliability is essential in remote areas. If the compressor fails, the winzes would completely flood within 48 hours. Compressor specifications are shown in Table II.

Table III. Operating parameters of the compressor

Free Air Delivery (FAD)	31.5 to 34.6 m^3/min
Working pressure	5 to 10.3 bar
Regulatory system features PACE technology, allowing for the electronic adjustment of pressure flow combination via a digital controller	

Ventilation of the winzes

Ventilation of the winzes was conducted utilising 15kW fans and 550mm flexible ventilation ducting, as depicted in Figure . As a standard, the ventilation was kept within 12m of the face. A re-entry period of 30 minutes was used before workers would re-enter the winze to commence pumping.

Figure 4: Ventilation in winze

During winzing operations, ventilation posed no real concerns, and the ventilation system worked well.

Dewatering of winze

Ground water was initially intersected some 15m below surface. The project first used electric spindle and pneumatic water pumps for dewatering. Spindle pumps failed early due to flooding of the winzes, poor electrical connections, and unreliable repairs. As a result, the mine stopped using the electrical spindle pumps and relied on the pneumatic diaphragm pumps (Figure 5). These pumps managed fissure water but often broke due to mud, silt, and pebbles entering the diaphragms. The pneumatic pumps also could not handle heavy rainwater (Figure 4), which resulted in delays while the winzes had to be pumped dry before development activities could resume. A further delay caused by flooding of the winzes was the washing of fine material down into the winze, necessitating the loading out of sticky mud at the bottom of the winze. Depending upon the intensity and duration of the rain, development in the winze could be delayed for a day to several days.

Figure 5: Examples of the winzes flooding after heavy rain

Figure 6: Dewatering the winze with the pneumatic double diaphragm pump

DISCUSSION AND COMMENTARY

The winzes were initially designed to provide early access to the orebody. This necessitated steep inclinations of 45 degrees that later transformed into 55 degrees due to the unexpected change in the dip of the orebody. Notably, the short-term prospects of using the winzes as a means to commence early gold production transformed into a medium-term solution, with the original incline shaft being stopped for a number of reasons

Early on issues were identified and modifications required to sustain the development of the winzes. Due to the steepness of the winzes, the use of scraper scoops was ineffective as much of the blast rock fell out of the scraper scoop as the scoop traversed the uneven and undulating footwall of the winzes. To overcome this problem the scrape scoops were modified into buckets. A further unexpected issue was the intersection of groundwater within the winzes, as due to the water the blasted rock fines would bind and require pinch bars to breaking the up the fine material so that it could be loaded into the modified scoop with shovels.

An additional problem was keeping the correct inclination of the winzes. The mining teams found it difficult to maintain the 45 to 55 degree inclination and ripping of the footwall occurred far too often.

Admittedly, this was exacerbated by the fact that the mine surveyor could not provide grade lines for the mining crew and could only provide elevation at the winze face.

Two incidents occurred with personnel being struck by the scraper rope due to the winch operator operating the winch without being given the all clear from the miner. Minor accidents also occurred with slipping while travelling in the steep winze. The biggest concern was rolling rocks while traveling in the winze with one reportable accident occurring. These risks were mitigated by implementing and enforcing a system whereby the winch driver only operates the winch once permission is personally given by the miner. Cleaning the winze footwall was implemented as part of the initial "making safe" procedure at the start of morning and nightshifts.

Each winze advanced approximately 12m per month, which was below the target of 15m to 20m. This was mainly due to seasonal rain, breakdowns of the pumps, and ripping of the footwall due to off-grade development.

Each winze typically could support 10 to 12 tonnes per day, based on a dayshift (development drill and blast) and night shift cleaning.

In retrospect, an inclination above 30 degrees is difficult to achieve for untrained labour, and even for experienced miners. The additional development required for the reduction in the inclination should easily be made up in the increase of the productivity of mining at a lower inclination. In addition, the safety concerns of developing and operating a winze at an inclination above 30 degrees must not be underestimated.

REFERENCES

- MQA (2025) *Challenges and Opportunities for Small Scale Mining in the South African Economy*. Enterprises University of Pretoria for the Mining Qualifications Authority. Available at: https://mqa.org.za (Accessed: 27 November 2025).
- World Bank (2025) *A new era of renewal in artisanal mining*. World Bank Group. Available at: https://www.worldbank.org (Accessed: 27 November 2025).

Lance Alex Langton

Mining Engineer

Lance Alex Langton is a mining professional and emerging industry consultant with a strong focus on the development and optimisation of small- to medium-scale mining operations across Africa. With a practical foundation in mining operations, project evaluation, and resource development, he brings a solutions-driven approach to unlocking value in complex geological and operational environments.

Lance has built his experience across various facets of the mining value chain, including exploration support, project startup planning, operational improvement, and cost optimisation. He has demonstrated a particular interest in identifying underutilized or sterilised mineral resources and repositioning them into viable, revenue-generating assets. His work is informed by a deep understanding of African mining contexts, where regulatory, logistical, and socio-economic factors require adaptive and innovative strategies.

A key area of Lance's professional focus is the structuring and implementation of small-scale mining ventures. He is actively developing a niche capability in establishing modular, scalable mining operations that can be deployed efficiently with limited capital while maintaining compliance, safety, and environmental responsibility.

His approach integrates technical mining knowledge with entrepreneurial thinking, allowing him to bridge the gap between resource potential and commercial execution.

In addition to his technical capabilities, Lance is developing expertise in mining-related financial modelling, project feasibility analysis, and investment structuring. He is particularly interested in leveraging these skills to support funding readiness for junior mining projects and to facilitate partnerships between investors and operators. His goal is to contribute to a more inclusive and sustainable mining sector by enabling access to opportunities for emerging players in the industry.

Lance is also engaged in continuous professional development, with a focus on advancing his knowledge in areas such as mineral economics, underground and surface mining methods, and infrastructure planning. He is committed to aligning his work with broader industry trends, including sustainability, environmental stewardship, and the role of mining in supporting energy transition and urban development.

At the core of Lance's professional vision is the ambition to become a trusted advisor and operator capable of initiating and managing mining projects across diverse African jurisdictions. He aims to play a meaningful role in transforming mineral resources into long-term economic value, while contributing to job creation, skills development, and responsible resource management.

Lance's participation in the SAIMM conference reflects his commitment to engaging with industry leaders, sharing knowledge, and contributing to discussions on the future of mining in Africa. He brings a forward-looking perspective grounded in practical experience, with a clear focus on execution, innovation, and sustainable growth.

Industry update: DMPR guideline for the compilation of a mandatory code of practice to mitigate geotechnical risk in civil tunnels and underground spaces

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The Department of Minerals and Petroleum Resources (DMPR) is in the process of developing a new guideline for the compilation of a mandatory Code of Practice (COP) to mitigate geotechnical risk in civil tunnels and underground spaces. This involves thorough internal regulatory, legal review and approval processes. This new COP will be the fifth in a series of similar DMPR guidelines for the compilation of mandatory COPs to mitigate geotechnical risks within the mining sector, with the other four guidelines respectively focussed on hard rock tabular mining, underground coal mining, surface mining, and massive mining. The new COP will follow the same guideline layout and structure as the other guidelines in the series, but with a specific focus on the design and construction of civil tunnelling projects and other underground civil works, any subsequent maintenance and repairs during the operation of such schemes, and the requirement to maintain unused and abandoned civil tunnels and underground spaces in a safe and stable condition where such underground facilities are not permanently closed to prevent inadvertent access.

This paper provides an update on progress with the development of a new DMPR guideline for civil tunnels and underground spaces; reviews the implications of its implementation for engineering designers of civil tunnels and underground spaces, civil engineering contractors involved in its construction, and the owners and operators of such underground facilities, and provides guidance on DMPR processes to ensure compliance.

The paper furthermore focuses on risk mitigation strategies to be implemented during construction and commissioning of such underground schemes, as well as post-construction during scheme operation, and reviews guidance included for regular inspection by competent geotechnical engineering practitioners of such facilities. Implications for civil tunnelling works and underground spaces constructed prior to promulgation of these new guidelines, as well as the need to maintain (or alternatively, permanently close) unused / abandoned tunnels are also discussed.

Finally, the paper reviews other requirements incorporated in this new guideline for civil tunnels and underground spaces including long term planning requirements, defined geotechnical roles and responsibilities, and requirements for geotechnical review and oversight.

FOREWORD

Geotechnical risk presents an inherent danger to persons involved in civil tunnelling construction and underground space development as well as post-construction during operation and maintenance of such a scheme. Although numerous interventions have reduced overall accident numbers over the past decade, the industry focus has shifted to a 'zero harm' approach.

An initial tripartite task team to address geotechnical risk was established under the auspices of the Mining Regulations Advisory Committee (MRAC) in the late 1990s. This task team produced four guidelines for the compilation of a mandatory code of practice (COP) to combat rock-related accidents in four different types of mining method from 1996 to 2006, namely in tabular metalliferous mines (1996), underground coal mines (2003), surface mines (2004), and underground massive mining operations (2006), with the guideline for tabular metalliferous mines subsequently revised in 2002.

Following that, a detailed investigation was conducted as part of the Safety in Mines Research Advisory Committee (SIMRAC) Project SIM060201 (Rockfall Elimination) (Joughin *et al.*, 2011), based on which certain changes to geotechnical engineering practices and geotechnical legislation at mines (and by extension, in civil tunnelling and underground space development projects) were recommended. The Mine Health and Safety Council (MHSC) requested MRAC to revise the four guidelines in the light of the SIMRAC report, and in 2014, MRAC appointed a task team to review fall of ground regulations in the Mine Health and Safety Act (MHSA) and Regulations, and to update the guidelines accordingly. Work on the guidelines commenced in 2015, with various drafts of the guidelines going through three cycles of internal and legal review, public participation and regulatory approval processes since then, and more recently under the auspices of a Mine Occupational Safety Advisory Committee (MOSAC) Task Group. That said, final review and promulgation of the updated guidelines, and of the new guidelines to mitigate geotechnical risk in civil tunnelling and underground space development, are expected in 2026. At the same time, work to update MHSA fall-of-ground regulations and associated incident and accident reporting frameworks and forms, are continuing.

This paper aims to provide an industry update on the soon-to-be-promulgated new guidelines for the compilation of a mandatory COP to mitigate geotechnical risks in civil tunnelling and underground space development.

That said, please note that much of this paper is adapted directly from the new civil tunnelling guideline (DMPR, 2026). While specific citations are not repeated throughout, the authors acknowledge this source and make no claim of originality over that content.

LEGAL STATUS OF THE DMPR GUIDELINES FOR CIVIL TUNNELLING (adapted from DMPR, 2026)

In this paper, 'civil tunnelling', 'underground space development', 'civil tunnelling project', 'project', 'project scheme', or 'scheme' refers to the making, repairing, re-opening or closing of any subterranean tunnel (i.e., a civil engineering tunnel, or any other underground space) or any other operations necessary or in connection with such operations, as defined by a 'works' in the MHSA. In this regard, with reference to 102 Definitions in the MHSA, insofar as this relates to the discussion in this paper:

> *"**'mine'** means, when- (a) used as a noun- ... (iii) a works"*

> *"**'works'** means any place, excluding a mine, where any person carries out- ... (c) the making, repairing, re-opening or closing of any subterranean tunnel; or (d) any operations necessary or in connection with any of the operations listed in this paragraph."*

For the complete definition of a 'mine' and a 'works', readers are referred to 102 Definitions in the MHSA.

STRUCTURE OF THE DMPR GUIDELINE FOR CIVIL TUNNELLING

The new DMPR guideline for civil tunnelling follows a similar document structure to that of the other DMPR guidelines, namely:

- Part A: Introduces the guideline, explains its legal status, scope and objectives, provides general definitions and acronyms used, and lists the names of individuals who drafted or reviewed / updated the guideline;
- Part B: Provides an Author's Guide for compiling the COP;
- Part C: Sets out in detail the structure of the COP to be compiled, and the content to be covered in the COP; and
- Part D: Guides implementation of the COP and compliance therewith.

This paper focuses on the required structure of, and content to be covered in the COP in terms of Part C of the new DMPR guideline for civil tunnelling and underground space development.

COP STRUCTURE & CONTENT (adapted from DMPR, 2026)

The first four sections of Part C of the COP must include the following:

- Section 1: Project details and COP compilation and review dates to be shown on the title page of the COP;
- Section 2: A detailed table of contents to be included with the COP;
- Section 3: Prescribed compulsory notes which explain the legal status of the COP; and
- Section 4: The names, qualifications and experience of those serving on the COP drafting committee, and review committees, with signoff by all members of the respective committees – and importantly, note that:
    - The employer must consult with the relevant Health and Safety (H&S) structure or H&S representative on the project on the preparation, implementation, or revision of the COP; and
    - The committee must include a competent person (i.e., a geotechnical practitioner) as contemplated in Schedule 22.14.1(8) of the MHSA regulations.

Section 5 of Part C of the COP must include pertinent information on the following:

- Project / scheme location;
- Geological setting;
- Structural geological setting;
- Hydrogeological setting;
- Geotechnical setting including information on:
    - Soil types and their properties;
    - Intact rock, joints / fractures, and rock mass properties;
    - Identified ground behaviours and failure modes which potentially may impact the stability of the tunnel / underground excavation;
    - Virgin in-situ ground stress; and
    - Seismological setting;
- Civil tunnelling and underground space development / excavation methods and equipment to be used;
- Specific requirements for geotechnical incident analysis on the project, vis-a-vis:
    - The COP must include a history of geotechnical-related accidents and / or dangerous occurrences where civil tunnelling or underground excavations caused ground movements, vibrations, seismicity and / or subsidence which were reportable in terms of MHSA regulations in Chapter 23; and
    - The incident analysis must be revised / updated at least once every twelve (12) months during initial project construction, as well as during any later extension of the project scheme and / or when major repairs or upgrades are carried out.

Section 6 of Part C of the COP notes the requirement to include a list of definitions for any word, phrase or term with a meaning that is not clear, or which will have a specific meaning assigned to it in the COP. Existing and / or known definitions should be used as far as possible while avoiding jargon and abbreviations that are not in common use or that have not been defined. The list of definitions should furthermore also include acronyms and technical terms used in the COP.

Section 7 of Part C of the COP sets out risk management strategies to be employed on civil tunnelling and underground space development projects. It is important to note that this Section 7 deviates from that in the other guidelines in this series of DMPR for the compilation of mandatory COPs, to adequately provide for the different phases in the full life cycle of civil engineering projects. Section 7 in the civil tunnelling guideline therefore provides guidelines on required risk mitigation strategies for the following:

- During construction and commissioning of the project;
- Post-construction, during scheme operation and maintenance;
- Unlined, unsupported tunnels and underground excavations constructed prior to the promulgation of this guideline; and
- Unused, abandoned tunnels.

The civil tunnelling guideline lists examples of different types of civil tunnels and underground spaces as presented in Table 1, with suggested minimum inspection intervals post-construction, during scheme operation and maintenance, for different types of civil tunnels and underground spaces as presented in Table 2. In this regard, also note the following:

- Inspections must be carried out by a competent person appointed in terms of MHSA Regulation 14.1(8) (as amended) and other relevant geotechnical regulations, read with the requirements of MHSA Schedule 22, who has relevant experience in the design, construction, and maintenance / repair of such civil tunnelling works and underground spaces;
- Where appropriate, other experts must participate in the inspections covering engineering disciplines such as ventilation, lighting, lining condition surveys and structural evaluations, evaluation of hydro-mechanical installations, corrosion, etc.;
- The COP must be revised and updated whenever major instabilities or repairs are identified during such inspections;
- The proposed intervals in Table 2 are broadly aligned with international guidance, including from the International Commission on Large Dams (ICOLD), the Electric Power Research Institute Inc. (EPRI), the Permanent International Association of Road Congresses (PIARC), the US Federal Highway Administration (FHWA), as well as other relevant infrastructure safety frameworks and guidelines; and
- The suggested minimum inspection intervals in Table 2 are a baseline recommendation only, with the actual inspection interval of a civil tunnel or underground space to be based on a detailed geotechnical risk assessment of that tunnel / underground space, considering factors such as tunnel and underground space usage, public exposure, risk to critical infrastructure, infrastructure age, geotechnical setting, historical performance, etc.

In addition to the above, it is important to note that any unsupported tunnels (or unsupported sections of tunnel) and underground excavations constructed prior to promulgation of this civil tunnelling guideline which are used by employees on a project to perform their duties post-construction, during long term operation and maintenance of the project, must be clearly defined in the COP and the geotechnical risks assessed, with appropriate controls implemented (including installation of systematic support where required, and replacement of any old support units which have failed, or which are compromised by severe corrosion, etc.) to prevent exposure of employees to uncontrolled falls of ground and to any other significant geotechnical hazards in such areas.

Table 1: Examples of different types of civil tunnels & underground spaces (from DMPR, 2026)

Type of Tunnel	Examples
Water tunnels for water transfer, or for power generation, tunnels exposed to large surge loads	Water transfer, e.g., Orange-Fish Transfer Tunnel, LHWP Delivery Tunnel North, etc. Water supply, e.g., Northdene Tunnel in the Shongweni area in KwaZulu-Natal, etc. Pumped storage, e.g., Drakensberg Pumped Storage Scheme (PSS), Ingula PSS, etc.
Tunnels and shafts providing access to underground infrastructure	Access tunnels, declines and escapeways, e.g., at Drakensberg PSS, Ingula PSS, etc.
Rail tunnels	Critical infrastructure, e.g., Gautrain tunnels, shafts and station caverns, tunnels on the Richards Bay Coal Line, and on the Sishen-Saldanha Railway Line, the Hex River Tunnels, etc. Tunnels on other railway lines e.g., the Lindokuhle Tunnel in the eThekwini area, etc.
Road tunnels	Critical infrastructure / tunnels with high traffic volumes, e.g., Huguenot Tunnel, Strydom Tunnels, Waterval Boven Road Tunnel, etc. Other tunnels on roads with lower traffic volumes e.g., Daspoort Tunnel on R55 in Pretoria, etc.
Pedestrian tunnels	Excluding cut & cover surface structures.
Underground tourist attractions	Examples include: - Gold Reef City Underground Mine Tours; - Cullinan Underground Mine Tours; - Cape Town Underground Water Tunnel Tours; - Waterval Boven Cogwheeled Railway Tunnel; - The Bothongo Wondercave in the Cradle of Humankind, where access is provided via a steep decline stairwell followed by vertical shaft; - Other project sites (or portions thereof) where visitors are taken on underground tours e.g., Drakensberg PSS, Ingula PSS, walking tours through Durban Harbour Tunnel, etc.; and - Operational tunnels that are open to the public e.g., Northdene Tunnel in the Shongweni area in KwaZulu-Natal, etc.
Underground bunkers, for storage or military purposes	Underground bunkers for strategic fuel storage, military use, etc.
Sewer tunnels	E.g., Durban Harbour Tunnel, sewer tunnels in Johannesburg and Cape Town – but excluding micro-tunnels.
Utility tunnels	Stormwater, electrical, telecoms and HVAC tunnels in urban areas but excluding micro-tunnels and cut & cover surface structures, e.g., stormwater tunnels in Durban and surrounding suburbs, the Glenwood Services Tunnel in Berea Ridge in Durban, etc.
Emergency escape tunnels and shafts	Associated with rail, road, underground power stations / bunkers, or with high-risk industrial tunnels.
Abandoned tunnels	E.g., Waterval Boven Cogwheeled Railway Tunnel, Laing's Nek Railway Tunnel, De Doorns Railway Tunnel, old postal tunnels in Johannesburg, etc.

Table 2: Suggested minimum inspection intervals for different types of civil tunnels[1] & underground spaces (from DMPR, 2026)

Type of Tunnel	Suggested Minimum Inspection Interval (years)					Comments
	Unlined & Unsupported[2]	Brick / Stone Masonry Lined	Bolted & Shotcrete Lining	Cast-In-Situ Concrete / Precast Segmental Lining[3]	Steel Lining[3]	
Water tunnels for water transfer, or for power generation (i.e., pumped storage)	Ad hoc / as required e.g., because of a blockage, etc.	2–5		5-10	5-10	Aligned with international hydropower inspection protocols (e.g., ICOLD, EPRI); however, schedule more frequent inspections if there are known geotechnical concerns, if tunnels start leaking, etc.
Tunnels & shafts providing underground access	1–3	3–5		5-10	N / A	5 years if regularly used or critical; 10 years for rarely accessed stable structures.
Rail tunnels: Critical infrastructure Other tunnels on smaller rail lines	 1–2 1–3	 2–5 3–5		5-10	N / A	Adopt shorter intervals (2–3 years) for high-speed rail or for rail tunnels with high traffic volumes, the US standard is typically 2 years.
Road tunnels: Critical infrastructure / high-traffic tunnels Other tunnels on lower-traffic routes	 1–2 1–3	2–5		5-10	N / A	International guidelines (e.g., PIARC, FHWA) recommend 2–5 years, depending on usage and tunnel condition.
Pedestrian tunnels	1–2	2–5		5-10	N / A	Use shorter intervals for tunnels with high pedestrian traffic volumes or in urban locations.
Underground tourist attractions	0.5–1	1–2		2-3	N / A	Higher frequency of inspections warranted due to public exposure.
Underground bunkers, for storage or military purposes	1–2	2–5		5–10	N / A	Where actively used: 5 years minimum. Where unused: Facility-dependent but still at least every 10 years to manage long-term geotechnical risk.
Sewer tunnels	Ad hoc, as required because of a tunnel blockage, etc.					Practical limits to specifying regular inspection intervals given environmental and health-related risks when working in sewer tunnels.
Utility tunnels	1–2	2–5		5–10	N / A	Service continuity critical; inspections to be coordinated with service providers.
Emergency escape tunnels	1–2	0.5–1		5–10	N / A	High safety relevance, often subject to additional regulatory requirements.
Unused, abandoned tunnels	As for 'Underground tourist attractions' above – and if not implemented, then such abandoned tunnels must be permanently sealed and closed off to prevent public access.					Higher frequency warranted due to public exposure.

[1] Excluding micro-tunnels and pipe jacking projects.
[2] Access to be limited to a competent person appointed in terms of MHSA Regulation 14.1(8) (as amended) and other relevant geotechnical regulations, read with the requirements of MHSA Schedule 22 and / or emergency rescue / proto teams, with the necessary PPE and emergency equipment as may be appropriate; no access to be allowed to other employees or the public unless in case of an emergency evacuation of the underground works in absence of another safe escapeway.
[3] The frequency of these inspections should be increased from that shown in this Table 2 where warranted based on the corrosivity / aggressivity of water, liquid or pollutants transferred.

The new civil tunnelling guideline also sets the following risk mitigation measures for unused and abandoned tunnels that are left open and unsecured:

- Inspections by a competent person appointed in terms of MHSA Regulation 14.1(8) (as amended) and other relevant geotechnical regulations, read with the requirements of MHSA Schedule 22, must be carried out at minimum intervals as prescribed for 'Underground tourist attractions' in Table 2;
- The necessary repairs and maintenance identified during such inspections must be carried out diligently and expeditiously, to ensure the stability of the tunnel / underground excavation and safe access to the public;
- Public access to such unused, abandoned tunnel / underground excavation must be prevented until the required repairs and maintenance have been completed; and
- Most importantly, should these requirements not be complied with, such unused, abandoned tunnel / underground excavation must be permanently sealed and closed off to prevent public access.

Section 8 of Part C of the COP must cover the following aspects of the project in detail:

- A discussion of strategies and measures employed to ensure the overall stability of the project and to prevent unplanned / uncontrolled collapse of the tunnel or underground excavation, or portions thereof;
- Measures and strategies employed to address any potential impact of civil tunnelling and / or underground space development on adjacent infrastructure and public areas;
- Measures to address the potential impact of construction over, adjacent to, or on top of pre-existing civil tunnels and underground spaces, waste rock dumps, material stockpiles, etc.;
- Measures employed to ensure the integrity of accesses to / exits from the underground workings, service excavations and escapeways, and to protect employees against geotechnical risks associated with instability of such excavations;
- Present a geotechnical appraisal of the stability of the civil tunnels and underground excavations, and measures to protect employees against geotechnical risks associated with instability of such excavations, and to ensure appropriate methodologies and criteria are used for the design of stable civil tunnels and underground excavations, and for any modification or optimisation thereof;
- Must describe the philosophy and methodology used in the design of support employed in the different underground excavations and tunnels on the project in general terms;
- Must describe the design and implementation of an effective stormwater, flood control, and dewatering strategy aligned with the groundwater and flooding risk profile of the civil tunnelling or underground space development project – and covering at least the following:
    - Stormwater design management and flood control;
    - Underground excavation and tunnel intersections with open exploration / geotechnical boreholes;
    - Flood control against stormwater runoff from adjacent surface areas; and
    - Underground dewatering; and
    - Depressurisation;
- Must set out a risk-based monitoring strategy (taking into account anticipated failure modes and the scale thereof, the history of instability / failure in the tunnel, the time to failure, exposure of persons, equipment and infrastructure, etc.) to confirm the stability of the civil engineering tunnel or underground excavation, to ensure the safety of persons, and to validate the design input parameters, inclusive of support design strategies – and covering the following where applicable:
    - Blast vibration monitoring;
    - Deformation / closure monitoring (e.g., dedicated closure meters, crack meters, strain gauged rockbolts, (multi)point borehole extensometers (MPBXs), etc.;
    - Support performance monitoring (e.g., load cells, or strain-gauged rockbolts, etc.);
    - Visual monitoring (including photogrammetry, drones, etc.);

    - Subsidence monitoring (e.g., inclinometers, time domain reflectometers (TDRs), etc.); and
    - Groundwater monitoring (e.g., vibrating wire piezometers, open standpipes, monitoring of seepage zones, etc.);
- Must integrate mitigation and control strategies for significant geotechnical risks with overall project planning by:
    - Describing the provisions made for integrating mitigation and control strategies for significant geotechnical risks into the overall project planning process;
    - Defining the roles of the persons responsible for effective geotechnical design implementation (e.g., project manager, project resident engineer, Geotechnical Engineering Practitioner (e.g., project geotechnical engineer / engineering geologist), project geologist, project surveyor, etc.);
    - Setting out processes to be followed in the recording and archiving of all decisions, and must describe the implementation procedure adopted; and
    - Setting out appropriate sign-off procedures to be followed by the responsible persons to ensure approval of the design to be implemented, or modification / optimisation thereof;
- Must describe measures to ensure fit-for-purpose selection of equipment and civil tunnelling / underground excavation methods in relation to ground control strategies adopted, specifically in relation to equipment and materials used, and methods and procedures employed;
- Must set out measures to identify areas of elevated geotechnical risk – that is, areas where observed adverse conditions could result in a reportable incident or accident because of unplanned and uncontrolled falls of ground or instability – or e.g., when intersecting major geological structures (dykes, major faults and shear zones, etc.) or when excavating large underground excavations (e.g., power caverns, large span tunnels), etc.;
- Must incorporate pertinent geotechnical aspects in a project's long-term operational and maintenance plans, during the project's service design life and beyond that where appropriate;
- Must set out the applicable geotechnical roles and responsibilities as required in terms of MHSA Regulation 14.1(8) (as amended) and other relevant geotechnical regulations, read with the requirements of MHSA Schedule 22;
- Must describe review and oversight processes to be followed and review cycles adopted in the finalisation and approval of geotechnical designs and recommendations, layouts, the COP, procedures and / or programmes, etc., as adopted on the civil tunnelling or underground space development project;
- Must set out measures to ensure that training as per Section 10 of the MHSA is done in relation to geotechnical hazard awareness and addressing of geotechnical risks; and
- Must set out a process to ensure that where there is reason to deviate from provisions of the COP (e.g., when experimenting with excavation and support layouts, sequences, and / or support systems), such deviation is carried out in a manner which addresses all geotechnical risks.

ROLES & RESPONSIBILITIES OF GEOTECHNICAL ENGINEERING STAFF (adapted from DMPR, 2026)

The updated DMPR Guidelines for the compilation of COPs to mitigate geotechnical risk on mines, or in this case, on civil tunnelling and underground space development projects, now includes an annexure which sets out the roles and responsibilities of geotechnical engineering staff employed on the project. In this regard, note that the various competencies and staff positions have been given generic names, and it is accepted that the same competency / position may be called something different on different mining operations or civil tunnelling projects – for example:

- A **Strata Control Observer** could mean an assistant geotechnical officer on an underground, massive mining operation, or a geotechnical assistant / technician on a civil engineering tunnelling project;

- A **Strata Control Practitioner** could mean a geotechnical officer on an underground, massive mining operation, a geotechnical technician on a surface mining operation, or a graduate engineering geologist or geotechnical engineer on a civil engineering tunnelling project;
- An **MHSA Regulation 14.1(8) (as amended) Geotechnical Engineering Practitioner** could mean a geotechnical engineer on an underground, massive mining operation or on a civil tunnelling project, a shaft rock engineer on an underground, narrow tabular mining operation, or a rock engineer on a surface mining operation; and
- An **MHSA Regulation 14.1(8) (as amended) Geotechnical Engineering Manager** could mean a chief rock engineer on an underground, narrow tabular mining operation or on a surface mining operation, or a principal geotechnical engineer or geotechnical design manager on a civil tunnelling project.

That said, the roles and responsibilities as defined for these different competencies / positions on a civil tunnelling or underground space development project as set out in the DMPR guideline annexure, are as follows:

- Strata Control Observer – see Table 3;
- Strata Control Practitioner – see Table 4;
- MHSA Regulation 14.1(8) (as amended) Geotechnical Engineering Practitioner – see Table 5; and
- MHSA Regulation 14.1(8) (as amended) Geotechnical Engineering Manager – see Table 6.

Table 3: Roles and Responsibilities of Strata Control Observers in civil tunnelling & underground space development (from DMPR, 2026)

Conduct inspections and audits to check the safety and condition of access tunnels and adits, underground excavations and working places.
Collect data for the calculation of density and compliance of installed primary and secondary support.
Assess quality of support work completed by contractors.
Inspect and comment on drilling patterns, charging and timing, sockets, effectiveness of smooth wall blasting, compliance to re-entry procedures, cleaning / mucking out and support installed.
Communicate with contractors and other service department personnel, both verbally and by means of populated checklists / field sheets or basic reports.
Inspect and assess ground conditions and installed support, identify hazards, communicate to line supervisor and contractor, and recommend additional support for identified local geotechnical hazards as per support standard.
Assist senior geotechnical engineering staff with the investigation of minor incidents and accidents (e.g., non-LTI) caused by rock-related instability (falls of ground and / or rock bursts), as well as cases of changes in, or unusual, rock mass condition or behaviour.
Check that support units are installed as specified (underground checks) and assist senior geotechnical engineering staff in checking that support units meet quality specifications (store yard checks).
Participate in start-up assessments as part of a cross-functional team.
Provide general support to the Geotechnical Section / Department, comply with departmental procedures and maintain relevant administrative and filing systems.
Install basic ground deformation monitoring instruments and / or warning devices. Collect monitoring and instrumentation data for processing and analysis.
Assist senior geotechnical engineering staff with preparation for planning meetings.

Table 4: Roles and Responsibilities of Strata Control Practitioners in civil tunnelling & underground space development (from DMPR, 2026)

Conduct routine, ad-hoc or requested inspections to examine, monitor and assess the safety, stability and condition of access tunnels and adits, underground excavations and working places.
Investigate incidents caused by ground-related instability and assist with accident investigations (e.g., LTI) caused by ground instability (falls of ground and / or rock bursts, etc.). Investigate cases of changes in, or abnormal ground conditions or behaviour.
Participate in baseline, continuous and issue-based risk assessments as part of a cross-functional team.
Collect, capture and process geotechnical data (e.g., core logging, field testing, sampling and coordination of laboratory testing, face mapping), maintain a geotechnical database. Assess geotechnical conditions based on processed geotechnical data.
Inspect installation and assess quality of ground support work completed by site personnel and / or contractors. Investigate requests and assess need for support work to be conducted by project personnel and / or contractors, either by recommending appropriate support or by escalating the request to senior geotechnical engineering staff as appropriate.
Where required, prioritise and schedule the workload and work output of project personnel and / or contractors.
Assist senior geotechnical engineering staff by carrying out ground stability analyses (e.g., planar, wedge, toppling failure).
Install instrumentation to monitor ground deformation and / or rock mass behaviour and support performance as part of the overall ground control monitoring strategy. Where required, record, review and interpret results.
Monitor activities relating to the civil tunnelling or underground space development process including drilling patterns, charging and timing, sockets, effectiveness of smooth wall blasting, compliance to re-entry procedures, cleaning / mucking out and support.
Provide on-the-job coaching to project personnel and supervisors, and contractors' personnel where appropriate, during workplace inspections.
Provide ground control-related awareness coaching to junior project personnel and service department personnel, and contractors' personnel where appropriate.
Assist senior geotechnical engineering staff and / or participate in regular construction progress and planning meetings.
Provide routine input into regular construction progress and planning meetings.
Assist with the compilation and / or updating of the COP to mitigate geotechnical risk on the project and assist with the compilation and / or revision of ground control-related standards and procedures.
Where applicable, manage the activities and outputs of junior geotechnical engineering staff.
Check that support units meet quality specifications (store yard checks, field testing and / or laboratory testing where needed).
Comply with statutory reporting requirements to MHSA Regulation 14.1.8 Competent Person. Comply with departmental procedures and standards, and maintain relevant administrative and filing systems.
Monitor and report on compliance to the COP to mitigate geotechnical risk on the project and associated standards and procedures.
Participate in investigations of relevant new technology and monitor trials.
Communicate with production and other service department personnel, both verbally and by means of detailed written reports.

Table 5: Roles and Responsibilities of Geotechnical Engineering Practitioners (as per MHSA Regulation 14.1(8) (as amended) in civil tunnelling & underground space development (from DMPR, 2026)

Manage geotechnical data collection methods such as mapping, logging and sample testing by geotechnical staff, external parties or personally. Review basic analyses and interpretation of geotechnical data by junior geotechnical engineering staff, and / or conduct advanced analyses as appropriate. Assess and define the geotechnical environment.
Design access tunnels and adits, underground excavations and service excavations / underground caverns, vertical / inclined shafts and underground chambers as part of a multi-disciplinary team. Design support where required. Reconciliation / optimisation of excavation and support design.
Conduct routine, ad-hoc or requested inspections to examine, monitor and assess the safety, stability and condition of access tunnels and adits, underground excavations and service excavations / underground caverns, vertical / inclined shafts and underground chambers, and working areas.
For Areas of Elevated Risk, advise the manager regarding the prescription of additional measures to reduce the level of ground-related risk.
Investigate reportable incidents and accidents caused by ground-related instability as well as cases of changes in, or unusual, ground conditions or behaviour.
Conduct baseline, continuous and issue-based risk assessments as part of a cross-functional team and recommend control strategies.
Participate and provide specialist input in all planning meetings, based on sound geotechnical principles and relevant geotechnical data. Compile associated documentation.
Participate and provide geotechnical input into activities relating to the civil tunnelling and underground space development process including drilling patterns, blast designs, smooth wall blasting strategies, re-entry procedures, cleaning / mucking out and support.
Keep abreast of advances in technology, manage investigations and trials of relevant new technology.
As part of the project's COP Drafting / Revision Committee, assist with the compilation and / or updating of the COP to mitigate geotechnical risk on the project, and assist with the compilation and / or revision of ground control-related standards and procedures.
Identify significant geotechnical hazards, identify geotechnical domains and classify Geotechnical Domains / Design Sectors, develop design and control strategies for the different Geotechnical Domains / Design Sectors identified.
Where applicable, manage the activities, outputs, performance and career development of junior geotechnical engineering staff within area of responsibility.
Communicate with production and other service department personnel, and contractors' personnel where appropriate, both verbally and by means of comprehensive written reports.
Design and implement systems and processes to monitor ground deformation behaviour / rock mass behaviour and support performance, analyse results and issue appropriate recommendations.
Provide on-the-job coaching to project personnel and supervisors, and contractors' personnel where appropriate, during workplace inspections.
Where applicable, manage and coordinate the workload and work output of project personnel and / or contractors.
Provide ground control-related awareness / geotechnical awareness coaching to senior production and service department personnel, and contractors' personnel where appropriate.
Assist training personnel with compilation of appropriate ground control-related / strata control related training for different levels of project personnel.
Register and maintain membership with an appropriate professional body (i.e., institution, association, etc.), voluntarily participate in the activities of relevant professional bodies.
Perform limit equilibrium and numerical modelling, back-analyse case studies, calibrate existing models and predict future rock mass response, integrate findings to optimise project design.
Where required, manage on-site support quality assurance programmes.
Develop and manage departmental procedures and maintain relevant administrative and filing systems.
Assist the project manager, chief design engineer, design manager or resident engineer with preparation of geotechnical budgets and monitoring of related expenditure.

Table 6: Roles and Responsibilities of Geotechnical Engineering Managers (as per MHSA Regulation 14.1(8) (as amended) in civil tunnelling & underground space development (from DMPR, 2026)

Align functional strategy of geotechnical department (e.g., in a civil engineering consulting practice, or at a civil engineering construction company) with the company's business strategy.
Provide functional oversight and assurance for company governance policies, procedures, standards, compliance and risk management insofar as it relates to geotechnical engineering.
In consultation with executive management, compile strategies regarding excavation stability and appropriate design criteria, layouts, excavation sequence and support designs (where applicable).
Establish monitoring, recording and reporting systems which will ensure that relevant geotechnical information is timeously provided to the planning and production departments, design engineering teams and / or contractors.
Compile strategy for the acquisition, processing, interpretation and management of geotechnical data.
Provide guidance to geotechnical, planning, project personnel, design engineers, and / or contractors in defining the geotechnical environment, excavation stability and design criteria adopted, layouts, excavation sequence and support requirements.
Investigate major incidents and accidents (e.g., fatal) caused by ground-related instability / rock-related instability (falls of ground and / or rock bursts), as well as cases of changes in, or unusual, ground conditions / rock mass conditions or behaviour. Guide and support on-site geotechnical engineering staff during accident investigations and enquiries.
Review departmental functions, activities and outputs (i.e., departmental audits) to ensure alignment with company and departmental strategies and procedures.
Analyse investigation results and statistics relating to company-wide ground-related accidents and incidents. Determine trends and root causes, recommend pro-active preventative strategies.
Ensure that Codes of Practice are compiled for every civil tunnelling and underground space development project within the company as per the relevant DMRE Guideline and conduct periodic reviews of the Codes of Practice and related standards and procedures.
Approve any deviations from the schedule of geotechnical engineering inspections.
Compile a quality assurance strategy for support elements used in different civil tunnelling and underground space development excavations and operations.
Communicate and liaise with geotechnical engineering staff on company-wide and / or adjacent shafts / civil tunnelling and underground space development projects regarding geotechnical matters of mutual interest.
Communicate regularly with company and project management regarding factors affecting tunnel and underground excavation stability, such as large collapses, major falls of ground, seismic activity and / or rock burst incidents (where applicable).
Keep abreast of and advise management and geotechnical engineering staff of advances in technology, leading practice and new processes, initiate and monitor investigations and trials of relevant new technology, practices and processes.
Register and maintain membership with an appropriate professional body (i.e., institution, association, etc.), voluntarily participate in working groups and committees of relevant professional bodies.
Prescribe requirement for the effective administration and filing of departmental outputs to comply with legislative and company governance requirements, audit effectiveness of system in place and optimise if required.
Provide guidance to project geotechnical engineering staff and / or training personnel regarding appropriate ground control-related training for different levels of project personnel.
Provide geotechnical-related awareness coaching to company management and senior project management.
Provide a mentoring and guidance role to senior geotechnical staff within the company in terms of technical advancement, skills development and career progression.
Compile company-wide strategies for staffing and management of the activities, outputs, performance and career development of geotechnical staff, in accordance with the specific risk profile of every civil tunnelling and underground space development project within the company.
Where applicable, propose and / or review geotechnical budgets and monitor related expenditure.

IMPLEMENTATION OF THE NEW CIVIL TUNNELLING GUIDELINE

It is clear that engineering designers of civil tunnels and underground spaces, and the civil engineering contractors appointed to construct these tunnels and underground spaces, will have to collaborate to ensure compilation of a COP that satisfies all the requirements of the new and soon-to-be-promulgated DMPR guideline for civil tunnelling and underground space development, given the wide scope and detailed content required.

Furthermore, owners and operators of such underground facilities need to take cognisance of the requirements of this new civil tunnelling guideline, in terms of:

- Risk management and mitigation during the different phases of the project's service design life and beyond that where appropriate;
- Setting appropriate intervals for inspections during the operational life of the facility – see Table 2;
- Timely compliance with maintenance and repair requirements in such tunnels and underground spaces;
- Maintaining unused, abandoned tunnels in a stable and safe condition where these are to be left open to the public – or otherwise, prevent public access by securely closing off unused and abandoned tunnels that are not being maintained; and
- Keeping the DMPR informed of any civil tunnelling construction and underground space development works (including extensions to existing project schemes), and of any major repairs or upgrades required during the operation of such a project scheme.

The new civil tunnelling guideline, once promulgated, will furthermore require implementation of a regular oversight mechanism by the DMPR, which should include:

- Setting up a register of civil tunnels and underground spaces which fall under the auspices of the DMPR in terms of the MHSA;
- Establishing and maintaining names and contact details of the owners and operators of such civil tunnels and underground spaces;
- As is done for operating mines in South Africa, fulfil the normal DMPR oversight functions as required in terms of the MHSA (e.g., in-person site audits, COP reviews, accident investigations, etc.) during initial project construction, as well as during any later extension of the project scheme and / or when major repairs or upgrades are being carried out;
- Participate in inspections of civil tunnels and underground spaces where appropriate; and
- Finally, fulfil DMPR oversight functions as required in terms of the MHSA to ensure unused, abandoned tunnels are maintained in a stable and safe condition where an owner or operator chooses to leave these open to the public – or otherwise, ensure that such unused and abandoned tunnels which are not maintained, are securely closed off to prevent public access.

CONCLUDING REMARKS

This paper provided an update on progress with the development of a new DMPR guideline for civil tunnels and underground spaces, reviewed implications in terms of its implementation, and emphasised risk mitigation strategies to be complied with during construction and commissioning of civil tunnelling and underground projects, as well as post-construction during scheme operation. The paper reviewed guidance included for regular inspection of civil tunnels and underground spaces by a competent Geotechnical Engineering Practitioner. It also discussed specific requirements regarding civil tunnelling works and underground spaces constructed prior to promulgation of this new guideline, as well as the need to maintain (or alternatively, permanently close) unused / abandoned tunnels. Finally, the paper presented the roles and responsibilities of geotechnical staff employed on civil tunnelling projects as defined in the new DMPR guideline and touched on requirements for geotechnical review and oversight.

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REFERENCES

Mine Health and Safety Act and Regulations, Act No. 29 of 1996, as amended.

DME 16 / 3 / 2 / 5 A1. 2000. Guideline for the Compilation of a Mandatory Code of Practice on Mine Residue Deposits.

DME 16 / 3 / 2 / 1-A3. 2002. Guideline for the Compilation of a Mandatory Code of Practice to Combat Falls of Ground and Rock Burst Accidents in Tabular Metalliferous Mines.

Mineral and Petroleum Resources Development Act, Act No. 28 of 2002 as amended.

DME 16 / 3 / 2 / 1-A4. 2003. Guideline for the Compilation of a Mandatory Code of Practice to Combat Falls of Ground Accidents in Underground Coal Mines.

DME 7 / 4 / 118-AB4. 2004. Guideline for the Compilation of a Mandatory Code of Practice to Combat Falls of Ground and Slope Instability Related Accidents in Surface Mines.

DME 16 / 3 / 2 / 1-A5. 2006. Guideline for the Compilation of a Mandatory Code of Practice to Combat Rockmass Failure Accidents in Massive Mining Operations.

Joughin, W.C., Nezomba, E., Rwodzi, L., & Jager, A.J. 2011. A Risk Based Approach to Enhancing Support Design in Bushveld underground Mines. Final MHSC Project Report No. SIM060201 Track B.

Unreferenced DMPR Guideline. 2026. FINAL DRAFT: Guideline for the Compilation of a Mandatory Code of Practice to Mitigate Geotechnical Risk in Civil Tunnelling & Underground Space Development.

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Gerhard Keyter is a civil engineer who specialised in geotechnical engineering in civil engineering and mining. Over the past 30 years, he has worked on, and led engineering teams involved in the design of open pit mines, railway cuttings, box cuts for adit portals and in pit crushers, other surface excavations, slimes dams and waste rock dumps, civil engineering tunnels, large hydropower caverns including large diameter surge shafts and chambers, mine tunnels, access and ventilation shafts, ore passes, and other underground mining excavations including crusher chambers, workshops, and main dewatering sumps. He has furthermore led an investigation into the root causes of a 2020 slope failure accident at a large open pit in South Africa and has also been involved in several mine closure studies.

Gerhard has been involved in projects in South Africa, Botswana, Burkina Faso, the Democratic Republic of Congo, Eritrea, Ghana, Guinea, Lesotho, Malawi, Mali, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe, as well as projects in Australia, Brazil, Chile, China, India, Panama, and Russia. Since 2015, Gerhard has served on Mine Health & Safety Council (MHSC) Mining Regulations Advisory Committee (MRAC) and Mining Occupational Safety Advisory Committee (MOSAC) Task Groups tasked with:

- Reviewing South African Mine Health & Safety Act (MHSA) fall of ground regulations & associated incident/accident reporting requirements; and
- Reviewing and updating the DMPR's Guidelines for the Compilation of Mandatory Codes of Practice for the Mitigation of Geotechnical Risk on South African Mines.

Design considerations and construction strategies for the uMkhomazi water project phase 1

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The uMkhomazi Water Project Phase 1 (uMWP-1) aims to augment water supply to the uMngeni Water Supply System (MWSS) in KwaZulu-Natal to address long-term regional water demand. A key component of the scheme is a 34 km waterway tunnel driven primarily by tunnel boring machines (TBMs), connecting the uMkhomazi intake to the Baynesfield outlet. The project presents several design and construction challenges, particularly due to the constraints of working within a relatively small 3.5 m internal diameter tunnel.

This paper outlines the main engineering strategies developed to manage these challenges, with preliminary design work completed to date, focused on practical solutions for tunnel logistics, including muck removal, segment transport, sequencing of construction activities, and the efficient use of equipment within the limited tunnel space. These aspects are essential in deriving workable construction methods for these long, small-diameter TBM tunnels. The paper also summarises options for TBM removal at the Baynesfield outlet, which represents a major project milestone with implications for programme, cost, and interfaces with downstream infrastructure.

Overall, the study highlights the importance of coordinated planning, effective logistics, and careful sequencing during the preliminary design phase to better manage construction risks and ensure long-term operability in complex tunnelling projects.

Keywords: TBM Tunnelling, Small-Diameter Tunnels, Long-Distance Tunnelling

INTRODUCTION

The uMkhomazi Water Project Phase 1 (uMWP-1) forms part of a long-term regional water security strategy in KwaZulu-Natal, South Africa. The project is being implemented by the Trans-Caledon Tunnel Authority to augment the existing uMngeni Water Supply System with water from the uMkhomazi river. This system supplies water to urban centres, industrial facilities, and agricultural areas.

At the core of uMWP-1 is a 34 km long bulk water conveyance tunnel extending from the uMkhomazi river intake works to the Baynesfield outlet. This water transfer tunnel represents one of the most significant components of the overall uMWP-1 infrastructure programme.

The tunnelling works comprise a combination of conventional drill-and-blast (D&B) excavations and mechanised tunnel boring machine (TBM) drives. The main tunnel elements include (Figure 1):

- D&B tunnels and adits, including:
  - uMkhomazi tunnel intake (uMTI) connecting tunnel;
  - uMkhomazi TBM access adit (uMAA);
  - Midway TBM access adit (MAA); and
  - Baynesfield tunnel outlet (BTO) connecting tunnel.
- TBM tunnels, comprising:
  - TBM Drive 1 (TBM1): From the uMkhomazi intake to Midway; and
  - TBM Drive 2 (TBM2): From Midway to the Baynesfield outlet connecting tunnel.
  -

Figure 1. Tunnel alignment and project overview.

Excavation is predominantly mechanised using aTBM, with a finished internal diameter (ID) of 3.5 m. The tunnel's combination of long alignment and relatively small diameter presents distinctive engineering and logistical challenges. Constraints associated with the small-diameter tunnel include restricted space for TBM operation, backup systems, conveying infrastructure, ventilation ducts, electrical services, and emergency access. Over the 34 km tunnel, even minor inefficiencies can accumulate, significantly affecting programme performance.

Given the long TBM drive lengths, breakthrough does not represent the end of construction risk exposure. TBM2 removal at the Baynesfield outlet constitutes a programme-critical operation with direct implications for construction sequencing, downstream interface works, and commissioning milestones. The selected TBM2 removal methodology therefore forms an integral component of the preliminary design, as delays or inefficiencies during this phase could disproportionately impact overall project delivery and associated timelines.

Design Considerations and Constructability Integration

Hydraulic Requirements

The selected 3.5 m ID is governed by hydraulic design, including discharge capacity, flow velocity limits, and head loss optimisation. This diameter balances hydraulic performance with capital efficiency but also defines a strict construction envelope. Unlike large-diameter tunnels, where space allows flexibility, the current configuration requires precise spatial coordination of all systems within the available tunnel cross-section.

Constructability as a Primary Design Consideration

In long, small-diameter tunnels, constructability must be treated as a primary design variable rather than a secondary validation exercise. All systems, including ventilation, electrical reticulation, communications, dewatering lines, mucking infrastructure, and segment transport must operate concurrently within a highly constrained spatial envelope. The long tunnel alignment magnifies the impact of operational inefficiencies. Downtime events, maintenance delays, or supply interruptions that may be manageable in shorter drives become programme-critical in long tunnel drives. Accordingly, system reliability, maintainability, and logistical resilience were adopted as core design objectives from the preliminary design stage.

Spatial Constraints and Cross-Sectional Optimisation

Within a 3.5 m ID tunnel, the segmental lining defines a strict geometric boundary within which the TBM shield, erector, backup gantries, and service systems must operate. Careful cross-sectional planning is therefore critical to ensure safe, efficient, and uninterrupted TBM operations. The tunnel cross-section must accommodate:

- Backup gantries;
- Transport systems, segment delivery and muck removal;
- Ventilation and booster stations; and
- Utilities, service lines, and instrumentation.

Figure 2 illustrates a representative tunnel cross-section.

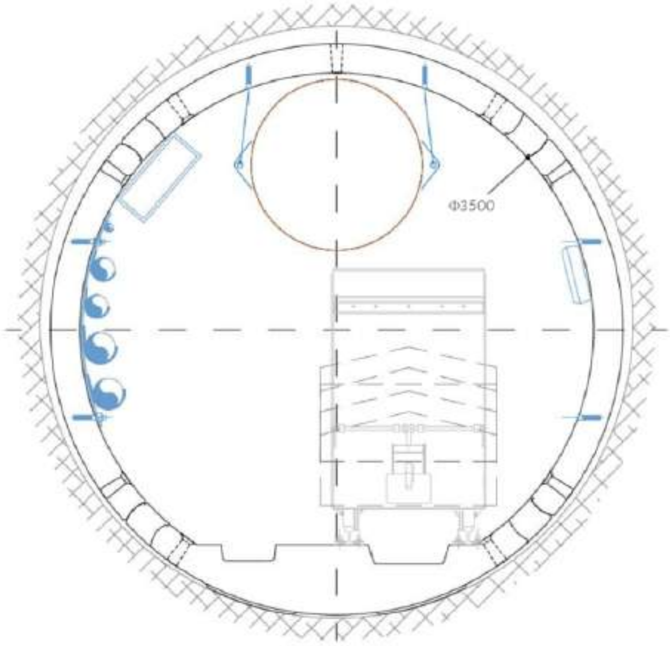


Figure 2. Typical tunnel cross section.

Multi-service vehicles (MSVs) were evaluated as a potential integrated logistics solution for combined segment delivery and muck removal within the main tunnel drives. However, they were found to be incompatible with the available spatial envelope. A fully loaded MSV requires a raised ramp system of approximately 0.8 m in height, leaving insufficient clearance for ventilation ducting, fixed services, and emergency egress provisions.

By contrast, locomotive-hauled rail wagons provide a significantly lower loading profile (approximately 0.5 m lower than equivalent MSV configurations), allowing integration of essential services while maintaining required safety clearances. The geometric constraint imposed by the 3.5 m ID therefore directly informed the selection of a rail-based logistics system.

TBM Logistics and Construction Sequencing

The extended tunnel length and restricted 3.5 m ID impose significant constraints on construction logistics and sequencing. In long single-access drives, advance rate stability is governed primarily by the interaction between muck removal, segment delivery, and concurrent service installation. Logistics planning was therefore integrated into the early design phase to ensure geometric compatibility, operational efficiency, and programme reliability.

Muck Removal Strategy
For a long tunnel, muck removal capacity directly governs achievable TBM advance rates. In a small-diameter tunnel, the available cross-sectional envelope limits the configuration of transport systems and fixed services.

Rail-based haulage using locomotive-hauled wagons was identified as the best geometrically viable solution within 3.5 m ID. Alternative systems, including MSVs, were evaluated but found to be incompatible with the available spatial envelope. Increasing the diameter to accommodate MSV ramps would require a minimum ID of approximately 4.5–5.0 m, materially affecting excavation volumes, lining quantities, hydraulic capacity, and capital cost.

Segmental Lining and Transport Logistics
Precast segmental lining provides ground support and ensures long-term hydraulic performance consistent with bulk water conveyance requirements. Within a 3.5 m ID tunnel, segment handling operations are constrained by limited working space in the TBM shield tail gap and the configuration of backup gantries.

Segment geometry will be optimised to balance structural performance, durability, individual unit weight, and erection efficiency. Design considerations include lifting constraints within the shield envelope, minimisation of manual intervention, and reduction of ring build cycle duration. Segment transport to the TBM will be undertaken using locomotive-hauled rolling stock. Train configuration and segment palletisation will be designed to optimise payload efficiency while maintaining braking performance and operational safety over extended haul distances.

Given that muck removal and segment delivery share the same rail infrastructure, logistics sequencing is subject to continuous cycle modelling to minimise production interference and avoid rolling stock congestion along the single-access alignment.

Access Adit Gradient Constraints
The TBM access adits are designed at gradients of approximately 8% for operational and long-term access efficiency. Conventional rolling stock cannot operate on such steep gradients, so alternative segment delivery systems were evaluated:

- Rubber-tyred locomotives: Limited by gradient, working space, and wet conditions within the adits; operational reliability is uncertain;
- Rack-and-pinion (cog-wheel) trains: Fully feasible within 3.5 m ID tunnels; provide traction on steep gradients, integrate with standard rail in the main tunnel, and eliminate the need for transfer caverns; and
- Winch-assisted systems: Impractical when considering access adit lengths of approximately 1 km (uMAA) and 3 km (MAA) respectively, due to safety concerns, regulatory restrictions, and mechanical risk.

Based on this assessment, cog-wheel trains were selected as the preferred solution for the steep access adits, ensuring continuous, reliable segment delivery while maintaining required safety and tunnel clearances.

Construction Sequencing and TBM Cycle Integration
The stability and efficiency of TBM advance rates along the tunnel are constrained by a tightly integrated framework encompassing excavation, lining erection, maintenance planning, and logistics coordination. Continuous monitoring and preventive maintenance scheduling reduce the likelihood of unplanned breakdowns, which can cause significant downtime, particularly on long tunnel drives. All supporting service systems, including ventilation, muck handling, and segment delivery infrastructure, will be synchronised with TBM operational cycles to minimise idle time. For single-shield TBMs, bore and segment erection cycles are performed sequentially, typically requiring approximately 50 minutes per complete cycle. In contrast, double-shield TBMs allow concurrent bore and segment ring construction, reducing the cycle to approximately 25–30 minutes.

These operational characteristics underscore that logistical support, particularly segment delivery and muck removal, is the primary determinant of sustained advance rates in long, small-diameter tunnel drives, often outweighing the influence of excavation mechanics alone.

Tunnel Diameter Sensitivity Assessment
A sensitivity study was undertaken to evaluate the technical and economic implications of increasing the tunnel ID from 3.5 m to 4.7 m. The assessment considered impacts on TBM performance, logistics efficiency, access adit functionality, geotechnical risk exposure, and overall capital cost. The objective was to determine whether a larger diameter would materially improve constructability and programme certainty sufficiently to justify the additional expenditure.

Technical Impacts
Increasing the tunnel ID to 4.7 m would materially expand the internal spatial envelope available for logistics and services. The main technical advantages identified include:

- **MSV passing ramps:** The increased cross-sectional area would allow installation of raised passing ramps for MSVs, enabling simultaneous movement of segment delivery and muck removal vehicles. This would reduce reliance on single-track rail cycles and mitigate congestion risk in long tunnels.
- **Improved service segregation:** Greater diameter facilitates clearer separation between mobile plant corridors and fixed infrastructure such as ventilation ducts, electrical reticulation, grout lines, and communication systems. Improved segregation enhances operational safety and simplifies maintenance access.
- **Enhanced maintenance accessibility:** Additional working space within the TBM shield and backup gantries would improve access for inspection, cutterhead interventions, and mechanical repairs, potentially reducing maintenance intervention duration and improving overall equipment utilisation.
- **Reduced internal congestion**: Greater clearance decreases the risk of physical conflicts between rolling stock, personnel, and fixed services, particularly during peak logistics cycles.

Despite these advantages, TBM excavation performance would remain largely unchanged. Bore cycle duration is primarily governed by cutterhead torque, thrust capacity, rock mass characteristics, and segment erection time; parameters not significantly affected by moderate increases in tunnel diameter. The production cycle assessment indicates that the net improvement in sustained advance rate would be limited to approximately 5% if the tunnel diameter is increased. In long tunnels, logistics constraints can often be mitigated through alternative systems, such as cog-wheel rail solutions, without enlarging the tunnel diameter.

Economic Assessment
Increasing the ID from 3.5 m to 4.7 m results in a substantial increase in excavation volume due to the quadratic relationship between diameter and cross-sectional area. The larger profile would require:

- Increased excavation quantities;
- A larger TBM and associated plant;
- Higher segmental lining volumes (i.e., number of segments) and reinforcement quantities;
- Increased muck handling and surface disposal requirements;
- Expanded portal and shaft geometries; and
- Enhanced surface logistics infrastructure.

High-level cost estimation indicates that these factors collectively increase base construction cost by approximately 20%. When compared with the estimated ~5% improvement in advance rate, the economic benefit of a shorter construction duration does not offset the additional capital expenditure. The modest programme acceleration achievable with a larger tunnel diameter therefore does not justify the significantly higher upfront cost.

Moreover, the implementation of rack-and-pinion (cog-wheel) segment transport in steep access adits effectively mitigates the primary logistical limitation associated with the 3.5 m ID configuration. This approach preserves production continuity without requiring tunnel enlargement.

Accordingly, both technical and economic evaluations confirm that the 3.5 m ID remains the optimal configuration for the uMWP-1 project. This diameter satisfies hydraulic performance objectives while maintaining capital efficiency, if logistics integration and sequencing are carefully managed.

TBM Breakthrough and Removal at Baynesfield

Strategic Importance

The TBM2 breakthrough at the Baynesfield outlet represents a critical milestone in the overall programme. Unlike conventional short tunnels, breakthrough in a long tunnel does not signify completion of risk exposure, and TBM2 removal at Baynesfield constitutes a major engineered operation with significant implications for safety, programme continuity, and interface with downstream infrastructure.

The selected removal methodology directly affects:

- Programme duration;
- Scope and complexity of surface infrastructure;
- Safety exposure during dismantling;
- Interface with downstream outlet structures; and
- Timing of final hydraulic commissioning.

For long, small-diameter tunnels, TBM removal must be treated as an integrated design decision rather than a terminal construction activity, as delays or inefficiencies during this phase can disproportionately affect overall project delivery.

Constraints Imposed by Tunnel Diameter

The 3.5 m ID imposes significant limitations on underground TBM dismantling operations. The restricted cross-sectional space constrains lifting geometry and equipment manoeuvrability, requiring careful planning of TBM extraction sequences.

Furthermore, after breakthrough, the TBM remains embedded within the precast segmentally lined envelope, limiting overhead clearance for major component extraction.

TBM Removal Options Overview

Three principal strategies were evaluated for the removal of TBM2 at the Baynesfield outlet:

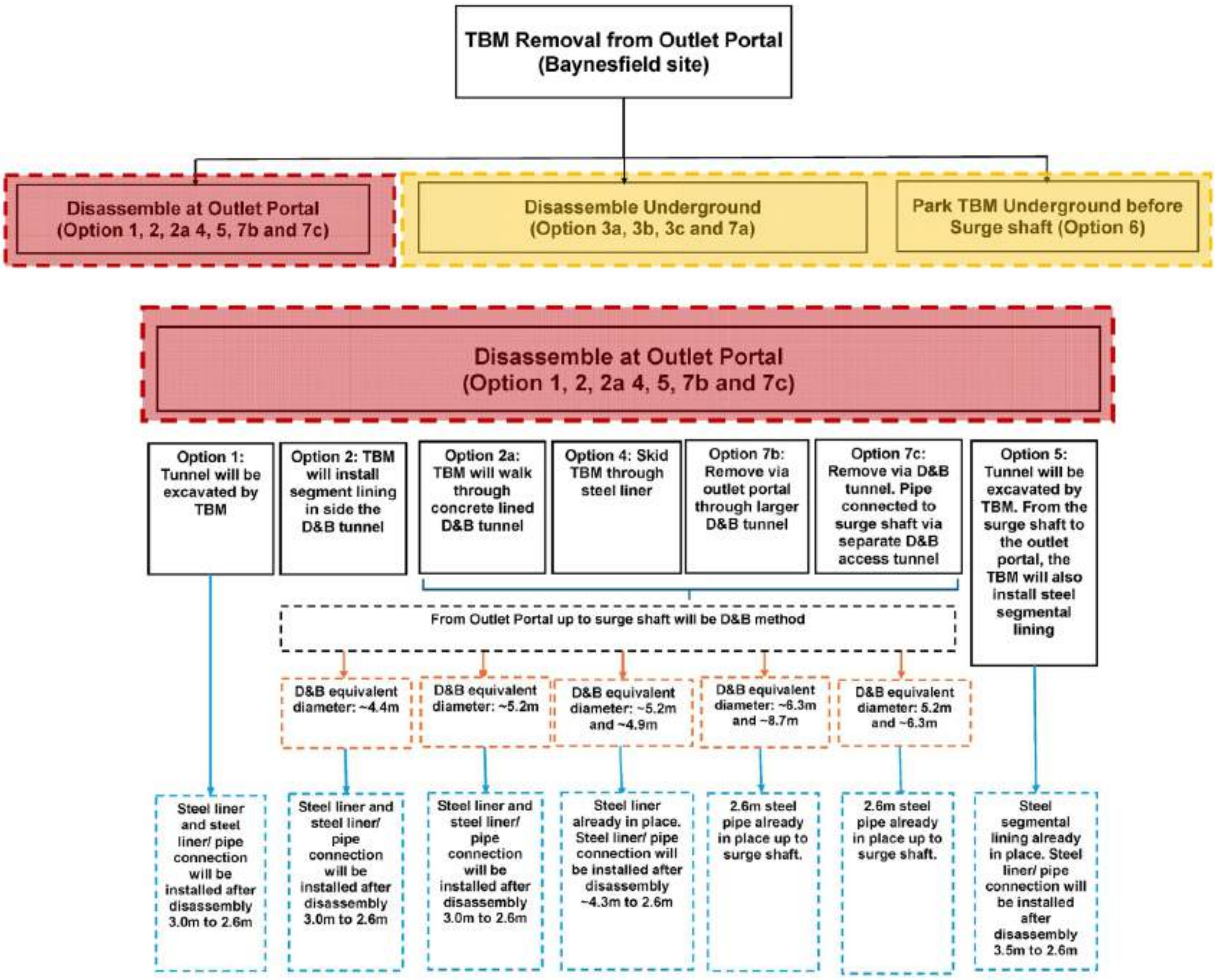
- **Strategy 1 - Surface disassembly at the Baynesfield outlet portal:** TBM2 is driven, walked, or skidded to the outlet portal, where disassembly occurs on surface within the outlet portal open cut, thereby minimising underground dismantling activities. This strategy minimises confined-space dismantling and simplifies lifting operations through conventional crane access. However, surface disassembly requires additional space within the open cut at the outlet portal and early integration with the outlet civil works.

- **Strategy 2 - Underground disassembly:** TBM2 is dismantled within a purpose-designed disassembly chamber located at the base/just upstream of the surge shaft. TBM components and the backup train are removed through one or a combination of the following routes:
  - The surge shaft;
  - The Baynesfield outlet connecting tunnel;
  - Reversing through the waterway tunnel and the Midway TBM access adit; and
  - A combination of these routes (e.g., shield removed via surge shaft or connecting tunnel, backup train removed via waterway tunnel and Midway TBM access adit).

  This approach reduces surface footprint and shaft diameter requirements but increases underground complexity. Confined-space dismantling introduces elevated safety exposure, extended dismantling duration, complex temporary lifting systems, and greater schedule uncertainty. Engineering controls such as temporary lifting frames, rail-based extraction systems, and enhanced ventilation are required to manage these risks.

- **Strategy 3 - Permanent burial / abandonment:** The TBM2 shield machine is driven offline and abandoned just upstream of the surge shaft and permanently sealed in, while the backup train is removed via the waterway tunnel and Midway TBM access adit.

Figure 3 presents a schematic comparison of the three strategies, highlighting tunnel cross-section requirements, disassembly chamber configuration, extraction routes, surface footprint implications, and interaction with downstream outlet structures. The schematic provides a consolidated visual framework supporting the multi-criteria analysis (MCA) carried out to compare the above TBM removal options, and clarifies the operational, structural, and sequencing constraints associated with the respective options.



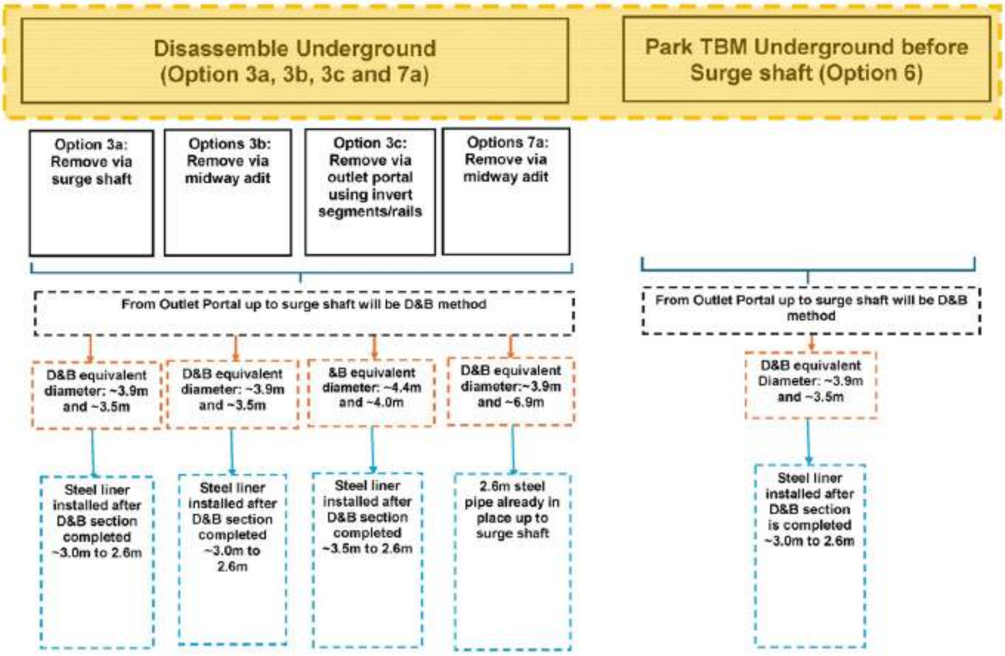


Figure 3. Overview of TBM removal options at Baynesfield outlet.

Comparative Engineering Assessment

The evaluation considered key factors including capital cost, programme duration, safety exposure, operational interface, and long-term asset implications. The assessment of the three TBM removal strategies is summarised as follows:

- **Surface disassembly (Strategy 1):** Offers the highest safety margin during dismantling and minimises confined-space exposure. Requires early integration with civil works and controlled open-cut geometry.
- **Partial underground dismantling (Strategy 2):** Reduced surface footprint but increased underground labour exposure, extended dismantling duration, temporary works complexity, and higher schedule uncertainty.
- **Burial in place (Strategy 3):** Avoids complex extraction but introduces long-term inspection, hydraulic transition, and lifecycle management concerns incompatible with a permanent strategic water asset.

Overall, the assessment confirmed that safety exposure and programme reliability outweigh marginal reductions in the required civil construction footprint.

Integration with Downstream Infrastructure

The selected TBM removal strategy at Baynesfield directly affects outlet structure sequencing and downstream construction logic. Timing of TBM breakthrough, dismantling operations, and component extraction must be coordinated with:

- Downstream concrete works;
- Hydraulic control structure installation;
- Bulkhead construction and tie-in; and
- Final hydraulic commissioning.

Misalignment between tunnelling completion and surface contractor activities can lead to redesign of outlet geometry, temporary works conflicts, restricted crane access, or inefficient double handling of structural elements. Early confirmation of the preferred TBM removal strategy therefore mitigates interface risk, reduces the likelihood of redesign, and ensures coherent sequencing between underground works and downstream civil construction.

Removal Options and MCA

To provide a structured and objective evaluation, a multi-criteria analysis was undertaken, assessing options derived from the three TBM removal strategies against five weighted criteria:

- Design and constructability;
- Financial implications;
- Social and environmental considerations;
- Programme impact; and
- Risk and uncertainty.

The weightings reflected programme certainty and safety exposure as primary evaluation considerations, recognising the disproportionate impact of removal delays in long-drive projects.

The MCA identified one of the options derived from Strategy 1, which incorporates an enlarged D&B outlet connecting tunnel with extension of the 2.6 m ID pipeline to the bulkhead interface, as the preferred solution. This option demonstrated the most balanced performance across constructability, cost efficiency, safety exposure reduction, environmental impact, and schedule reliability.

Programme and Risk Implications

Analysis indicates that inadequate planning of TBM removal can introduce disproportionate schedule risk relative to the relatively short duration of the removal operation itself. In long tunnels, project momentum, resource allocation, and contractual milestone achievements are often linked to TBM breakthrough completion. However, if TBM removal logistics are not properly integrated into the project design and construction planning, delays can occur due to limited shaft capacity, restricted lifting operations, or complex dismantling procedures. Such delays may affect demobilisation activities, delay subsequent construction works, and potentially extend the overall project programme. For this reason, TBM removal should not be treated as a final construction activity but rather as an integral design consideration influencing shaft sizing, tunnel alignment geometry, lifting capacity, and structural detailing from the early stages of project development. This approach reduces programme uncertainty and ensures that the transition from excavation to completion activities can occur without introducing unnecessary schedule risk.

Risk Management and Constructability Integration

Constructability was prioritised as a primary design driver rather than a secondary verification exercise. Logistics consideration, spatial coordination reviews, and maintenance accessibility studies were integrated into the preliminary design process.

Key construction risks identified include interruptions to the muck removal system, segment supply disruption, major TBM mechanical failure, and groundwater inflow events. Mitigation measures include incorporating system redundancy where feasible, implementing preventive maintenance strategies, and providing contingency access provisions to enable rapid intervention during critical events.

CONCLUSIONS

The uMWP-1 represents a technically demanding example of long-distance, small-diameter TBM tunnelling for bulk water conveyance. The combination of a 34 km tunnel length and a 3.5 m ID create a configuration in which logistics coordination, spatial constraints, and construction sequencing become primary determinants of programme certainty.

The paper shows that sustained productivity in long, small-diameter tunnels is governed largely by logistics efficiency rather than TBM bore cycle performance alone. Over long alignments, even minor inefficiencies in segment delivery, muck removal, or maintenance planning can accumulate into significant schedule impacts.

Tunnel diameter sensitivity analysis indicates that increasing the ID to 4.7 m would provide only modest production gains (approximately 5%) while increasing capital costs by approximately 20%. The 3.5 m diameter therefore remains technically and economically justified when supported by rail-based muck removal, cog-wheel segment delivery in steep access adits, integrated logistics planning, and preventive maintenance strategies.

The paper also highlights the importance of integrating TBM removal strategy during preliminary design. Early planning improves constructability, reduces confined-space risks, and enhances programme reliability. The multi-criteria assessment identified surface-based TBM disassembly as the most balanced solution.

Overall, the project demonstrates that constructability-driven design, integrated logistics planning, and early consideration of TBM removal are essential to achieving programme certainty in long water conveyance tunnels

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References

Abell, R., Smith, J. & Turner, P., 2016. Long-drive TBM logistics and productivity optimisation. Tunnelling and Underground Space Technology

Bilfinger Berger, 2014. Construction logistics in long TBM tunnels. In: Proceedings of the World Tunnel Congress.

Chapman, D., Metje, N. & Stark, A., 2017. Introduction to Tunnel Construction, 2nd ed. London: CRC Press.

Herrenknecht AG, 2017. Tunnel Boring Machines: Technical Description and Operational Considerations. Technical Report.

International Tunnelling Association, 2015. Guidelines for Mechanised Tunnelling. ITA Working Group Report.

Maidl, B., Herrenknecht, M., Maidl, U. & Wehrmeyer, G., 2013. Mechanised Shield Tunnelling. Berlin: Ernst & Sohn.

Polihali Water Transfer Tunnel Project, 2021. Access adit transport and segment supply strategies. In: Proceedings of the International Conference on Tunnelling.

Robbins Company, 2019. TBM Shield Maintenance and Removal Guidelines. Technical Manual.

Siemens AG, 2020. Rubber-Tyred Rail Systems for Steep Inclines. Technical Bulletin.

Swiss Federal Railways, 2018. Gotthard Base Tunnel Project Documentation: TBM Operational Considerations for Long Drives. Technical Report.

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Construction method evaluation for ventilation and surge shafts on the uMWP-1 water transfer tunnel project

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This paper presents an overview of the key considerations governing construction method selection for ventilation and surge shafts for the Phase 1 water transfer tunnel of the uMkhomazi Water Project (uMWP-1). The uMWP-1 project site is located between Impendle and Hopewell, south of Pietermaritzburg in KwaZulu-Natal, and includes two ventilation shafts (1.5 m finished diameter, with depths of 125 m and 190 m, respectively) and one surge shaft (5.0 m finished diameter and 110 m deep), to be constructed in Karoo mudrocks and dolerites.

Geotechnical characterisation of the shaft sites was undertaken using borehole logging, downhole wireline geophysical surveys, and laboratory testing. These investigations identified sequences of weathered and fresh shale, dolerite intrusions, structurally disturbed intervals, and variable groundwater conditions. Anticipated rock mass behaviour, together with structural data evaluated using Rocscience Dips and Unwedge, informed the evaluation of design risks and preliminary ground support requirements for shaft stability.

The paper compares shaft sinking methods, including reverse circulation (RC) drilling as the preferred method for the ventilation shafts, and alternative methods for the larger surge shaft. The discussion focuses on the suitability of these methods relative to anticipated ground conditions, groundwater, working footprint, cost and programme implications, and site-specific environmental constraints, particularly at the outlet end of the uMWP-1 transfer tunnel. Relevant precedent experience and comparable case studies are referenced where applicable.

The paper also considers the influence of logistical constraints, anticipated water inflows, and variable surface conditions on construction planning and risk management. Practical aspects of ground support, groundwater management, and spoil handling are discussed. The paper concludes with recommendations on method selection and risk mitigation, informed by the current investigations, precedent experience from similar shaft projects, and ongoing design of the uMWP-1 works.

INTRODUCTION

Project Context

The uMWP-1 project is being implemented by the Trans-Caledon Tunnel Authority (TCTA) to augment the uMngeni Water Supply System in KwaZulu-Natal with water from the uMkhomazi River. This paper focuses on the water conveyance infrastructure component, which comprises a 34 km water transfer tunnel with associated intake and outlet works. The project site is located between Impendle and Hopewell, south of Pietermaritzburg in KwaZulu-Natal.

The water transfer tunnel will be constructed using two tunnel boring machines (TBMs) operating from separate access adits to enable concurrent excavation. TBM Drive 1 extends 16.4 km from the uMkhomazi intake to the Midway access point, while TBM Drive 2 extends 16.1 km from Midway to the Baynesfield outlet. To support these extended TBM drives, the project requires three vertical shafts: two ventilation shafts to supply fresh air during construction, and one surge shaft to provide hydraulic transient control during operation of the uMWP-1 scheme. The shafts present particular design challenges due to their varying scales, the variable Karoo geology encountered, and environmental constraints affecting construction sequencing.

Table I summarizes the key parameters of the three vertical shafts. The ventilation shafts (VS1 and VS2) are relatively small with 2.0 m excavated diameter (1.5 m finished internal diameter) and extend to depths of 125 m and 190 m respectively, presenting opportunities for alternative construction methods not commonly employed in South African civil engineering practice. The surge shaft (SS), while shallower at 110 m depth, has a larger 6.0 m excavated diameter (5.0 m finished internal diameter) and must function as a permanent hydraulic structure during its design life. Additionally, the surge shaft location within a known breeding habitat area of the highly endangered blue swallow (*Hirundo atrocaerulea*) restricts construction to a six-month annual window (September to February), and places additional emphasis on programme-efficient method selection.

Table I: Shaft specifications and functions

Shaft	Location	Depth (m)	Excavated / Finished Internal Diameter (m)	Primary Function	Key Challenges
VS1	CH 6+720	125	2.0 / 1.5	Fresh air supply to the TBM1 drive during tunnel boring	Fractured zones, dolerite/shale mixed face
VS2	CH 27+556	190	2.0 / 1.5	Fresh air supply to the TBM2 drive during tunnel boring	6 m fault zone with expected high groundwater inflow rates
SS	CH 33+592	110	6.0 / 5.0	Surge pressure control during scheme operation	17 m weak fractured zone, blue swallow 6-month construction window

Design Approach & Scope

The design approach for the uMWP-1 shafts integrates geotechnical baseline reporting principles, as established by ASCE (American Society of Civil Engineers, 2022) and FIDIC for underground works, with the systematic construction method selection process outlined in ITACET Working Group 23 Guidelines for Shafts. The Geotechnical Baseline Report (GBR) (GKP Joint Venture, 2026) establishes anticipated ground conditions and defines contractual baselines for risk allocation, while the ITACET WG23 framework provides a structured methodology for evaluating alternative construction methods against project-specific constraints including ground conditions, geometry, programme, and environmental requirements.

The ventilation shafts serve primarily as construction infrastructure to support TBM operations, providing fresh air supply and emergency egress during the three to five-year tunnelling period. Although these shafts will form part of the permanent works for operational ventilation and maintenance access, their design criteria are governed by construction requirements rather than complex operational loading. Accordingly, the shaft design establishes baseline ground conditions and minimum dimensional requirements, including the 1.5 m finished internal diameter and verticality tolerances, while the final construction method remains the contractor's responsibility based on the conditions encountered. This also includes the decision on whether competent rock intervals can remain unlined or whether permanent lining will be required throughout.

The surge shaft, by contrast, is a permanent hydraulic structure that must withstand operational surge pressures, external groundwater loading, and satisfy stringent impermeability requirements over its design life. Its design and construction are intrinsically linked to the method of shaft construction selected as it influences achievable excavation tolerances, support installation sequencing, liner installation methodology, and programme duration.

This paper addresses the geotechnical characterisation of all three shafts, including the investigation approach, structural analysis using Rocscience Dips (Rocscience Inc., 2026) and Unwedge (Rocscience Inc., 2026), and ground behaviour assessment using the Ground Behaviour Type (GBT) framework. Construction methods are evaluated in accordance with ITACET WG23 (ITACET Working Group 23, 2019) methodology: reverse circulation drilling for the small-diameter ventilation shafts and raise boring versus conventional shaft sinking for the larger surge shaft. The comparison considers ground conditions to be encountered, programme implications, environmental constraints, surface footprint, and cost, together with practical considerations including ground support, groundwater management, and spoil handling.

Finally, although the design aims to provide contractors with clear geotechnical baselines, defined performance requirements, and reference construction methods that support informed method selection, competitive pricing, and equitable allocation of geotechnical risk, it is important to note that at the time of writing this paper, geotechnical investigations for the uMWP-1 site had only just concluded. Work continues on the geotechnical characterisation of these shafts as the tender design of the uMWP-1 scheme is being finalised, and it follows that the geotechnical characterisations as presented in this paper, may differ from that eventually presented in tender documentation being prepared for the uMWP-1 scheme.

Geological Setting

The project area is underlain by sedimentary rocks of the Karoo Supergroup, specifically the Ecca Group. The formations encountered along the tunnel alignment comprise predominantly of argillaceous rocks, including shales, mudstones, and siltstones with subordinate sandstone units, representing deep-water to deltaic depositional environments.

The sedimentary sequence has been extensively intruded by dolerite. These intrusions occur as massive sub-horizontal sills, ranging from a few metres to several tens of metres in thickness, and as sub-vertical to steeply dipping dykes with widths typically from 0.5 m to 30 m. The dolerites are characteristically very hard (UCS 180-250 MPa), abrasive, and crystalline, contrasting with the weaker sedimentary rocks (UCS 50-120 MPa). Contact metamorphism adjacent to intrusions has locally indurated the sedimentary rocks, creating zones of enhanced strength and durability, though the intrusion margins are typically fractured and altered.

Regional structural trends comprise predominantly sub-horizontal sedimentary bedding with prominent sub-vertical joint sets. Geological lineaments identified through aerial photographic interpretation and satellite imagery exhibit three dominant orientations: east-southeast to west-northwest (303° ± 30°), north to south (060° ± 20°), and southwest to northeast (005° ± 20°). These lineaments, manifested as faults, shear zones, fracture zones, and dolerite intrusions, exert primary control on rock mass quality and groundwater circulation.

The shaft locations exhibit this geological variability: VS1 consists predominantly of Volksrust Formation indurated shales with dolerite sills, VS2 is dominated by massive dolerite and a fault zone and faulted sedimentary strata, and the surge shaft is located entirely within Pietermaritzburg Formation shales and siltstones with a single dolerite sill. This geological diversity necessitates shaft-specific assessment of ground conditions and construction method suitability.

GEOTECHNICAL INVESTIGATIONS & CHARACTERISATION

Investigation Methodology

The geotechnical investigation for the uMWP-1 shafts comprised field investigations, downhole geophysical surveys, laboratory testing, and hydrogeological testing undertaken to characterise ground conditions and establish geotechnical baselines for design and contractual purposes.

A single HQ-size rotary core borehole was drilled at each shaft location, positioned at or near the planned shaft centreline and advanced beyond the anticipated shaft depth to characterise the rock mass below the shaft base and through the shaft–tunnel intersection zone. Borehole TTB7.6 at VS1 was drilled to 170.71 m, TTB27.5 at VS2 to 220.97 m, and TTB33.7 at the surge shaft to 110.44 m. Core recovery was generally excellent in fresh rock, but reduced locally within weathered, fractured, and faulted intervals, which were identified as potential construction challenges.

Wireline geophysical logging was completed in each borehole following drilling and included acoustic televiewer (ATV), optical televiewer (OTV), and natural gamma logging. These data supplemented the conventional core logging, supported lithological correlation, and provided the principal structural dataset for assessment in Rocscience Dips (Rocscience Inc., 2026) and Unwedge (Rocscience Inc., 2026).

Surface geophysical investigations, including electrical resistivity profiling, were also undertaken to provide context beyond the borehole locations, including overburden thickness, bedrock depth, lithological boundaries, dolerite intrusions, and potential water-bearing zones.

Laboratory testing was carried out on representative core samples to assess intact rock strength, density, porosity, abrasivity, durability, and swelling potential. Hydrogeological testing included packer testing, water level monitoring, and groundwater quality sampling. The hydraulic parameters derived from the packer testing were used to inform groundwater inflow estimates.

The geotechnical investigations carried out at shaft positions aimed to define characteristic geotechnical baseline conditions and provides a reasonable basis for design of the shafts; however, some uncertainty remains, specifically with respect to localised structural and hydrogeological variability.

ENVIRONMENTAL & SEASONAL CONSTRAINTS

Environmental constraints are particularly important at the surge shaft location, which lies approximately 500 m from a confirmed blue swallow nesting site. In accordance with the project Environmental Management Programme (EMPr), no construction activities are permitted during the breeding season from 1 March to 31 August. Construction is therefore restricted to an annual working window between 1 September and 28 February.

This seasonal constraint is a major driver in method selection for the surge shaft, as it places strong emphasis on programme efficiency, construction sequencing, and timely surface rehabilitation in addition to the geotechnical and hydraulic requirements of the shaft.

SHAFT STRATIGRAPHY & ROCK MASS CONDITIONS

The three shaft locations are located within different parts of the Karoo sequence and therefore exhibit materially variable ground conditions. This will influence anticipated excavation behaviour, support requirements, groundwater risk, and ultimately the suitability of alternative construction methods. A simplified summary of the stratigraphy encountered in the investigation boreholes drilled at each of the shaft locations is presented in Table II.

Table II: Comparative shaft stratigraphy and geotechnical conditions

Zone	Depth (m)	VS1 (Volksrust Formation)	VS2 (Dolerite - dominated)	SS (Pietermaritzburg Formation)
Overburden	0-20	17 m residual dolerite with corestones	1.7 m thin hillwash	0.3 m topsoil over 23 m weathered shale (R1-R2) with sample loss at 17-18 m
Upper section	20-50	Dolerite sill (17-23 m, R5), Volksrust shale (R4, RQD 77-90%)	Fresh massive dolerite (R6, RQD 85-100%)	Dolerite sill (23-41 m, R5), then shale (R3)
Middle section	50-100	Volksrust shale, RQD with variable, fractured zones at 28-29 m (RQD 0%) and 42-44 m (broken core); dolerite sill at 46-48 m	Fresh dolerite continues	Critical Zone 5 (56-73 m) weak shale (R2), approximately 21 fractures/m, incl. approx. 10 m of extremely fractured rock
Lower section	>100 to shaft bottom	Volksrust shale with RQD 37% near the tunnel intersection	Faulted sedimentary strata (96-123 m) containing a 6 m wide fault zone intersection at 117-123 m (RQD 15-30%), underlain by dolerite	Fresh shale (R3)

Ventilation Shaft 1 (TTB7.6): Indurated shale with thin dolerite sills

VS1 exhibits the most uniform stratigraphy of the three shafts. It comprises predominantly of Volksrust Formation indurated shale (strong, R4) interbedded with two dolerite sills at shallow depth (17-23 m and 46-48 m). The upper 17.1 m of residual dolerite overburden, including corestones will require casing through the superficial zone during shaft construction.

Rock mass quality indicates good to fair quality throughout most of the shaft depth. Three localised fractured zones represent potential construction challenges: a 0.6 m highly fractured interval at 28-29 m depth, a 2.2 m water-bearing broken zone at 42-44 m that required grouting during borehole drilling, and a 2.5 m fractured interval at 118-120 m approaching the tunnel intersection. These zones are anticipated to influence local stability and may reduce excavation rates and/or support demand.

Ventilation Shaft 2 (TTB27.5): Dolerite-dominated with fault zone

VS2 presents the highest overall rock mass quality of the three shafts. The shaft is dominated by fresh massive dolerite, representing approximately 85% of the shaft profile. The dolerite is generally very strong to extremely strong (R5-R6). RQD values of 85-100% indicating favourable excavation conditions through most of the shaft depth. The thin overburden (1.7 m) and minimal weathered zone (0-4 m) allow rapid establishment into competent bedrock.

The principal geotechnical challenge for VS2 is associated with faulted sedimentary strata between 96 m and 123 m depth, comprising of Pietermaritzburg Formation siltstone and mudstone. Within this interval, a 6 m wide fault zone intersection at 117-123 m depth is characterised by crushed to brecciated mudstone with very closely spaced jointing. The fault zone represents the main localised hazard for the shaft and is interpreted to be the principal contributor to the estimated groundwater inflow of approximately 11 L/s. Accordingly, VS2 is expected to remain relatively stable through most of the shaft depth, with support and groundwater control requirements likely to be concentrated within this faulted interval.

Surge Shaft (TTB33.7): Shale variable quality with extended weak zone
The surge shaft stratigraphy exhibits the greatest variability in rock strength and rock mass quality. The upper part of the profile comprises approximately 23 m of weathered Pietermaritzburg Formation shale, classified as very weak to weak (R1–R2), including intervals of completely weathered material with sample loss recorded during drilling at 17–18.3 m depth. These conditions indicate low intact strength, high weathering susceptibility, and elevated moisture sensitivity in the near-surface zone.

A competent dolerite sill occurs between 23 m and 41 m depth and is underlain by fresh to slightly weathered shale and siltstone. The critical interval for the surge shaft construction occurs between 56-73 m depth, where a 17 m interval of weak shale (R2 strength class) with very closely jointed fabric, averaging approximately 21 fractures per metre, and includes about 10 m cumulative thickness of extremely fractured rock. This extended zone of poor ground quality has significantly lower strength compared to the more competent shale (R3) above and below and represents the design-governing condition for both support requirements and construction method selection.

STRUCTURAL CHARACTERISATION & KINEMATIC ASSESSMENT

Structural assessment of the shaft excavations was based primarily on acoustic televiewer (ATV) and optical televiewer (OTV) data collected in the investigation boreholes. These surveys provided continuous discontinuity orientation data and were used to identify the principal structural sets at each shaft location. Field observations of bedding and lamination were used to confirm the broader geological fabric and to compare surface observations with the downhole televiewer-derived data.

The discontinuity data were analysed in Rocscience Dips to define the principal structural sets and to assess their orientation relative to the planned shaft excavations. The purpose of the analysis was to determine whether the observed discontinuities could contribute to structurally controlled instability, including sidewall block release, local wedge formation, and ravelling within weaker intervals. Rather than predicting exact failure volumes, the analysis was used as a screening tool to identify the structural conditions most likely to influence excavation behaviour, support requirements, and construction risk. This is consistent with the broader use of structural data in the paper to inform geotechnical risk assessment and construction method selection.

The interpreted structural framework across the three shaft locations is characterised by sub-horizontal to gently inclined sedimentary fabric, together with prominent steeply dipping jointing, consistent with the regional structural pattern identified from borehole televiewer data and surface geological observations. At VS1, these structures are expected to contribute mainly to local block release and ravelling within fractured shale and dolerite contact zones. At VS2, the structural regime is dominated by generally competent dolerite, but includes localised faulted sedimentary strata and a 6 m wide fault zone intersection that is expected to control the principal interval of structurally influenced instability and groundwater ingress. In the surge shaft, bedding-parallel weakness combined with closely spaced jointing within the weaker shale interval is expected to promote sustained loosening, local overbreak, and increased support demand. The structural assessment therefore confirms that, although all three shafts are influenced by similar regional discontinuity families, the engineering significance of those structures differs materially by shaft and depth interval.

The structural interpretation is particularly important in the critical intervals identified in the boreholes, including the fractured zones in VS1, the faulted interval in VS2, and the extended weak shale zone in the surge shaft. In these areas, the orientation and persistence of discontinuities may locally reduce stability and increase the need for support, groundwater control, or more conservative construction sequencing, refer to Table III below.

Table III: Summary of principal structural features and design implications

Shaft	Principal structural framework	Design implication
VS1	Sedimentary fabric with sub-horizontal to gently inclined bedding and steeply dipping jointing; localised fractured zones at lithological contacts	Localised structurally controlled instability is anticipated, mainly as block release and ravelling in fractured intervals
VS2	Predominantly competent dolerite containing steep discontinuity sets, with localised faulted sedimentary strata and a 6 m wide fault zone intersection	Structural risk is concentrated within the faulted interval, where instability and groundwater inflow are expected to be locally elevated
Surge shaft	Bedding-dominated shale/siltstone sequence with steep jointing and an extended weak, closely fractured shale interval	Structural conditions are expected to promote more sustained loosening and support demand than in the ventilation shafts

At the shaft–tunnel intersections, the interpreted structural sets may be assessed further using Unwedge (Rocscience Inc., 2026) to evaluate the potential for removable wedges under the more complex three-dimensional excavation geometry. This is particularly relevant for the surge shaft, given the larger intersection size and the greater potential for local wedge instability. Detailed Unwedge assessment is ongoing and will be used to refine intersection-scale support requirements during detailed design.

HYDROGEOLOGICAL CHARACTERISATION

The hydrogeological setting of the project area is characterized by low primary porosity and permeability within the argillaceous rocks of the Ecca Group, with groundwater occurrence and flow governed by secondary fracture networks. Groundwater is therefore expected to occur primarily in joints, bedding planes, lithological contacts, and fault zones. The dolerite intrusions may act both as relatively low-permeability barriers within massive sill and dyke interiors and preferential flow paths along fractured intrusion margins and contact zones.

Groundwater levels in the tunnel exploration boreholes indicate that the water table generally follows topography, ranging from approximately 95 m below ground level beneath topographic highs to 6 m below ground level in valley bottoms. At the shaft locations, conservative design groundwater levels correspond to hydraulic heads of approximately 123 m at the base of VS1, 186 m at the base of VS2, and 75 m at the base of the surge shaft. These values are considered conservative for design purposes and assume groundwater levels at or near ground surface. Preliminary monitoring indicates limited seasonal fluctuation, although ongoing monitoring will further refine the baseline understanding of recharge response.

As an initial indication, groundwater inflow rates to the shafts were estimated using the Jacob-Lohman equation for radial flow to a vertical cylinder. These inflow estimates were based on hydraulic conductivity values derived from packer testing, estimated hydraulic heads, and shaft geometry. Table IV summarizes the anticipated inflow rates. At the time of writing, transient groundwater modelling was ongoing to further refine these preliminary estimates.

Table IV: Expected groundwater inflows

Shaft	Depth (m)	Shaft Radius (m)	Hydraulic Head (m)	Hydraulic Conductivity, K (m/day)	Estimated Inflow (L/s)	Critical inflow zones
VS1	125	0.85	123	0.03	1.2	Fractured zones at 42 to 44 m
VS2	190	0.85	186	0.4 (fault zone)	11.0	Fault zone at 117 to 123 m
SS	110	3.0	107	0.03	1.2	Zone 5 at 56 to 73 m

GROUND BEHAVIOUR ASSESSMENT & DESIGN RISKS

Ground Behaviour Type Framework

The Ground Behaviour Type (GBT) framework provides a systematic basis for evaluating how the rock mass is expected to respond to excavation-induced stress relief, exposure, and groundwater changes, independent of the construction method used. Unlike conventional rock mass classification systems such as RMR (Bieniawski, 1989) or Q (Barton, et al., 1974) which describe rock mass quality, the GBT framework focuses on anticipated instability mechanisms and excavation behaviour. This distinction is critical for shaft design, where excavations in rock of good quality may behave unfavourably if structurally controlled failure mechanisms are present, while an excavation in poorer quality rock may remain stable in the absence of specific ground behaviours resulting in failure.

For the uMWP-1 shafts, GBT ratings were assigned using an integration of multiple data sources including borehole logging (RQD, fracture frequency, weathering grade, lithology rock mass quality indicators), structural assessment in Dips (Rocscience Inc., 2026), laboratory testing (strength, durability), hydraulic testing (permeability, inflow potential), and precedent experience from similar shaft construction projects in comparable geological settings, such as the Lesotho Highlands Water Project Phase 1B - Mohale Tunnel (Lesotho Highlands Development Authority, 2004) (Boniface, 2000). Each GBT was assigned a likelihood rating from 1 (almost impossible) to 5 (very likely), reflecting the likelihood of encountering that particular behaviour being encountered during shaft excavation.

The GBT assessment serves three main purposes in the current study. First, it identifies the dominant ground control mechanisms likely to govern shaft behaviour. Second, it supports construction method selection by highlighting behaviours that may be more readily managed by particular sinking methods. Third, it establishes the baseline interpretation of anticipated ground conditions for design purposes.

Anticipated Ground Behaviours in Shaft Excavations in Rock

Table V summarises the GBT assessment for excavations in rock in the respective shafts and includes only those behaviours rated 3 (unlikely but possible) or higher. Behaviours rated 1 (almost impossible) or 2 (very unlikely) were excluded from this summary as these are not expected to materially influence design or construction.

Several key patterns emerge from this GBT assessment. All three shafts exhibit a similar baseline potential for structurally controlled behaviour, with kinematic instability, blockiness and structural drilling-related instability all rated as likely. This is consistent with the regional jointing pattern within the Karoo sedimentary rocks and dolerite intrusions and precedent experience during the excavation/sinking of shafts in Karoo strata, and supports the importance of structural assessment in evaluating shaft stability.

The most adverse ground behaviours during shaft excavation is expected in VS2, in fault- and shear zones encountered in Borehole TTB27.5, and associated high groundwater ingress, all rated as very likely. These behaviours are associated mainly with faulted sedimentary strata between approximately 117 m and 123 m depth and a 6 m wide fault zone intersection, where broken ground, reduced strength, increased permeability, and lithological contrasts were encountered in Borehole TTB27.5. Although this interval represents only a small proportion of the total shaft depth, it is likely to constitute the main construction risk for VS2.

In the larger diameter surge shaft, poorer ground conditions are more distributed over the full depth of the shaft. Ravelling, poor durability, and structurally controlled loosening are all assessed as likely, particularly within the weak shale interval between 56 m and 73 m depth and the upper weathered shale profile. This extended zone of weaker rock is expected to have a greater influence on support demand, excavation sequencing, and construction method suitability than a shorter isolated fault zone.

Table V: Anticipated Ground Behaviour Types for the uMWP-1 shafts

GBT	Ground Behaviour / Failure Mechanism	VS1	VS2	SS	Key Design Consideration
GBT 1	Stable ground	4	4	4	Majority of depth, limited support required
GBT 2	Local/minor geological overbreak	4	4	4	Excavation tolerance and local support
GBT 3	Kinematic instability (sidewall wedges and/or key blocks)	4	4	4	Structural control and local support requirements
GBT 5	Blocky to very blocky ground	4	4	4	Relevant in dolerite sections, reduced support spacing
GBT 6	Ravelling in friable ground	4	3	4	Critical in fractured intervals and weak shale zones, particularly for Surge Zone 5
GBT 8	Shallow-seated rock mass shearing & yielding	3	4	3	Minor deformation potential in weaker intervals, VS2 fault zone
GBT 15	Poor durability(slaking)	4	2	4	Argillaceous rocks require limited exposure time
GBT 17	Wide fault/shear zones	3	5	4	VS2 fault zone is the dominant localised hazard, at 117-123 m
GBT 18 (boring)	Very hard, massive rock	n/a	n/a	5	High drilling resistance and higher cutter wear, especially in dolerite
GBT 19 (boring)	Structurally controlled blockiness in very hard rock	n/a	n/a	5	Potential breakout and local instability during advance
GBT 21	High groundwater ingress / inflow	3	5	4	Potentially significant inflows anticipated in the VS2 fault zone

Notes: Rating scale: 5 = Very likely, 4 = Likely, 3 = Unlikely but possible, 2 = Very unlikely, 1 = Almost impossible

Key Design Considerations

Although several behaviours are rated as likely, not all are equally significant in terms of design and method selection. The most important behaviours for the present study are structurally controlled instability, ravelling in weak ground, mixed-face conditions, faulted ground, and groundwater ingress.

Structurally controlled instability is anticipated in all three shafts and is associated with discontinuity orientation, persistence, and block geometry. Its practical significance lies in the potential for local block release, wedge formation, and overbreak, particularly where excavation is unsupported or support installation is delayed. This behaviour is therefore an important consideration in assessing construction methods which provide immediate confinement, allow rapid support installation and/or limit exposure such that the stand-up time of the excavation is sufficient to allow safe installation of primary support before shaft excavation is advanced further.

Ravelling and progressive loosening are most relevant to the fractured intervals in VS1 and, more significantly, to the extended weak shale interval in the surge shaft. In these zones, weak intact rock, close joint spacing, and poor interlock reduce stand-up time and increase the likelihood of progressive instability if exposure is prolonged. These conditions favour construction methods that permit early stabilisation and careful sequencing.

The fault zone and associated faulted sedimentary strata in VS2 introduce sharp contrasts in strength, structure, permeability, and excavation response over short distances. This combination of broken rock, groundwater ingress, and variable material in the fault zone, introduces potential construction risk over this depth interval.

Poor durability is most relevant in the argillaceous units of VS1 and in the surge shaft, where slaking and moisture sensitivity may lead to time-dependent deterioration of any exposed excavation surfaces. From a design perspective, this requires construction sequencing and support measures that minimise exposure time and prevent deterioration following excavation.

Overall, the GBT assessment confirms that while the respective shaft excavations all exhibit a baseline likelihood of structurally controlled behaviour, the dominant risks differ in character and concentration: VS1 is influenced mainly by localised fractured intervals, VS2 by a water-bearing fault zone within otherwise competent dolerite, and the surge shaft by a more extended weak and non-durable shale interval. These differences are central to both support planning and construction method selection.

SHAFT CONSTRUCTION METHOD EVALUATION

This construction method evaluation was undertaken in the context of the key geotechnical, hydrogeological, ground support, and programme risks identified for the respective shafts. Furthermore, for the 2.0 m excavated diameter ventilation shafts, the evaluation focused on methods suited to excavate such small diameter shafts. For the surge shaft with 6.0 m excavated diameter, the assessment considered methods appropriate for larger-diameter shaft construction, with due regard to the weak shale interval and the seasonal blue swallow environmental constraint.

Excavation of Shaft Collars in Soft Overburden
The upper sections of both ventilation shafts will extend through soft overburden (transported material, residual / completely weathered rock). The ventilation shaft collars will be excavated through these soft and weak materials making use of special construction techniques such as, for example, installation of secant pile walls, or using telescopic RC drilling techniques, with the most optimal method to be selected during detailed design.

Shaft Excavations in Rock - Ventilation Shafts
For the ventilation shafts, three principal construction methods were considered, namely: (1) reverse circulation (RC) drilling, (2) raise boring, and (3) conventional shaft sinking. Each method offers distinct advantages and limitations relative to the anticipated ground conditions, programme requirements, and cost:

- Reverse circulation (RC) drilling
  RC drilling employs a surface-mounted rotary rig with dual-wall drill pipe, allowing continuous excavation while drilling fluid transports cuttings to surface. The method is well suited to small-diameter shafts and offers particular advantages in deep shaft excavation where minimising personnel exposure at depth, reducing surface infrastructure, and maintaining efficient advance rates are important. In addition, the drilling fluid column provides hydrostatic confinement during excavation, which may assist in managing local instability in fractured or blocky intervals.

- Raise boring
  Raise boring a 2.0 m diameter ventilation shaft is technically feasible for the ventilation shafts. However, raise boring requires access to the shaft bottom which introduces practical and programme constraints given that (i) bottom access will only be established once the TBM has been driven beyond the ventilation shaft position, and (ii) raise boring the shaft then, will require tunnel boring works to stop for as long as raise boring and shaft support / final lining works continue.

- Conventional shaft sinking
  Conventional shaft sinking remains a proven and flexible method, particularly where local support installation is critical. However, 1.5 m finished diameter shafts are too small to excavate using blind sink methods, and the excavated shaft diameter will therefore have to be increased to say minimum 3 to 3.5 m to make this method of excavation feasible. The associated shaft construction costs will increase, and production rates will also be substantially lower than for the RC drilling alternative.

Based on this preliminary evaluation, RC drilling was selected as the preferred construction method for the uMWP-1 ventilation shafts in terms of programme efficiency, safety, limited surface footprint requirements, and suitability for the anticipated ground conditions. The method is used internationally to excavate ventilation and service shafts to substantial depth within a relatively small operational footprint. Where soft overburden or weak, friable material is encountered, RC drilling is used with telescopic casing to advance shaft excavations through such loose and/or unconsolidated materials to ensure hole stability. The method also offers environmental and logistical advantages, as the surface footprint is significantly smaller than that required for conventional shaft sinking infrastructure. This is beneficial in the rural project setting and reduces the extent of temporary site disturbance.

In VS1, fractured and water-bearing depth intervals may reduce advance rates locally but are unlikely to compromise overall method suitability. In VS2, the main challenge will be the shaft intersection with the faulted sedimentary strata at 117–123 m depth; however, given that this represents a relatively short section within an otherwise competent dolerite profile, it is considered manageable within an RC drilling approach, subject to appropriate contingency measures and contractor methodology.

Shaft Excavations in Rock - Surge Shaft
RC drilling has been used to excavate shafts of 4.5 m diameter or smaller, and the method evaluation for the 6.0 m excavated diameter surge shaft therefore focused on other feasible alternatives, namely: (1) conventional shaft sinking without a muck pass, (2) raise boring, and (3) conventional shaft sinking with a pre-RC drilled muck pass.

The surge shaft intersects the transfer tunnel some 300 m upstream of the Baynesfield tunnel outlet and it follows that access to the shaft bottom is required before raise boring can commence. This access constraint is particularly important when considered together with the blue swallow environmental restriction, which limits construction at the surge shaft site to a six-month annual window between September and February.

From a geotechnical perspective, the principal challenge is the extended weak, fractured shale interval between approximately 56 m and 73 m depth. This zone is expected to require sustained ground control measures to manage ravelling, structurally controlled loosening, and potential time-dependent degradation of weak argillaceous material. The larger shaft diameter also increases the significance of Conventional shaft sinking without a muck pass

- Conventional shaft sinking without a muck pass

  Conventional shaft sinking by drill and blast excavation is considered the reference construction method for the surge shaft at this stage. This reflects its greater flexibility for managing the anticipated weak ground conditions and its independence from prior tunnel access to the shaft bottom. The method allows excavation to proceed in controlled rounds, with direct observation of the exposed ground and installation of sidewall support as required. This is particularly advantageous through the weak fractured shale interval, where support requirements may need to be adjusted in response to actual ground conditions encountered during shaft sinking.

A further advantage is that shaft sinking from surface does not depend on completion of the tunnel to shaft base level before shaft excavation can commence. This makes it the more robust baseline method because it is less constrained by tunnel sequencing and provides the greatest flexibility for active ground control. Construction of the surge shaft is not on the overall critical path and the slower shaft sinking rate (when compared to raise boring) and potential programme risk as a result of the environmentally restricted construction window, is offset by the time available to complete this part of the works before TBM2 arrives at the Baynesfield outlet portal.

- Raise boring

  Raise boring remains a technically feasible alternative for excavation of the surge shaft and theoretically may show a reduced shaft excavation duration when considering typical raise boring rates. It will also minimise the surface footprint at the shaft location which is an important environmental consideration. However, raise boring is subject to two limitations, the first being the need for prior access to the shaft bottom, and the second being the potential for significant overbreak in highly jointed/fractured dolerite intervals, and in the weak fractured shale interval in the surge shaft excavation. Other issues include the potential for pilot hole deviation, reaming difficulties in the hard, highly jointed dolerite, and difficulties installing sidewall support in sections where extensive overbreak occurred.

  Accordingly, raise boring is considered an alternative should the contractor be able to demonstrate that constraints associated with shaft-bottom access requirements, construction sequence, and geotechnical risks can be satisfactorily managed.

- Conventional shaft sinking with pre-RC drilled muck pass

  A variant on the above shaft excavation methods is combining a conventional shaft sinking operation with a pre-RC drilled muck pass. This offers similar benefits to that offered by a conventional shaft sinking operation from surface, but with easier muck and groundwater seepage handling via the muck pass. As for raise drilling, however, the muck pass can only be employed once access has been established to the shaft bottom. It therefore suffers from the same programme constraints as the raise boring option.

The below construction method comparison for the surge shaft therefore reflects a trade-off between geotechnical flexibility and programme efficiency. Conventional shaft sinking provides the more conservative and geotechnically robust shaft excavation method because it allows direct management of the weak ground interval and does not depend on prior tunnel access to the shaft bottom. Raise boring may offer shaft excavation rate and surface footprint advantages, particularly in relation to the restricted environmental construction window, but its suitability remains conditional on shaft bottom access, construction sequence, and management of risks associated with highly jointed and fractured ground, and weak ground.

The comparative weighting exercise (see Table VII) indicates the highest nominal score for conventional shaft sinking, mainly because of programme advantages and better control provided by incremental excavation and timely ground support installation. For baseline design, conventional shaft sinking without a muck pass was therefore selected as the reference method.

That said, shaft sinking with a muck pass, and raise boring remain viable alternatives that may be preferred based on contractor-specific sequencing or programme considerations, provided that shaft bottom access and associated programme constraints and geotechnical risks are appropriately addressed.

Table I: Surge shaft method comparison matrix

Criterion	Weight	Conventional Shaft Sinking	Raise Boring	Conventional Shaft Sinking with pre-RC Drilled Muck Pass	Comment
Programme	35%	Slower excavation rate, but can commence on appointment, earlier shaft construction completion date	Faster, but subject to shaft bottom access first being established, effectively resulting in a later shaft construction completion date	Faster excavation rate than shaft sinking without muck pass, but subject to shaft bottom access first being established - as for raise boring	The requirement for earlier project delivery places greater emphasis on overall programme and schedule efficiencies
Ground control	25%	Excellent, sidewall support installed during excavation	Moderate, sidewall support installation post-shaft excavation	As for shaft sinking without a muck pass, albeit sidewall support can be installed earlier in an excavation lift due to easier mucking and shaft dewatering	Conventional shaft sinking offers better control and greater flexibility in highly jointed dolerite and weak shale
Cost	20%	Higher	Lower	Similar to shaft sinking without a muck pass, with the additional cost of drilling the muck pass being offset by easier mucking and shaft dewatering operations	Raise boring costs are typically 30 to 40% that of conventional shaft sinking, due to faster, less labour-intensive and safer mechanised operations
Surface footprint	10%	Larger	Smaller	Smaller than for shaft sinking without a muck pass, but larger than for a raise boring operation	Important environmentally constrained site
Safety	10%	Personnel working at depth in the shaft bottom	No personnel at depth during excavation; however, muck requires loadout at the shaft bottom during raise boring	Personnel working at depth in the shaft bottom AND muck requires loadout at the shaft bottom during shaft sinking operations	Raise boring offers a safety advantage
Weighted score:		**80/100**	75/100	79.5	

SURFACE CONDITIONS & WORKING AREAS

Surface conditions at the three shaft locations differ in terms of access, topography, land use, and available working area, and these factors influence site access, construction planning, temporary works layouts, spoil handling, and rehabilitation requirements.

VS1 is located at approximately 1,123 mamsl and is accessed via a provincial gravel road. The site is situated on gently sloping grassland. Spoil disposal is planned at a designated site approximately 2 km away.

VS2 is located at approximately 1,245 mamsl near the bottom of a relatively deep valley associated with erosion along the lineament of a local thrust fault. Access is provided via approximately 8 km of farm and plantation roads from the Baynesfield tunnel outlet portal. The site is situated within commercial forestry land, and shaft construction will require localised tree clearing and subsequent rehabilitation.

The surge shaft is located at Baynesfield at approximately 975 mamsl near the top of a small hill about 300 m upstream of the tunnel outlet portal. Access is via about 3 km of farm road from the Baynesfield tunnel outlet portal. The site lies within an active agricultural field and construction will require temporary suspension of crop production and subsequent rehabilitation. The natural veld immediately adjacent to the surge shaft location is considered a blue swallow habitat and associated environmental constraints apply. Eskom overhead powerlines are located approximately 200 m north of the site, but no direct conflict has been identified.

The anticipated working areas are relatively modest for the two ventilation shafts, particularly if constructed by RC drilling, whereas the surge shaft requires a larger construction footprint, especially if conventional shaft sinking is adopted. These differences are relevant to method selection, surface disturbance, and rehabilitation planning.

Table VII: Summary of surface conditions and working area requirements

Shaft/ Method	Reference Method	Estimated Footprint (ha)	Estimated Laydown Area (m^2)	Approximate Spoil Volume (m^3)	Principal Rehabilitation Requirement
VS1	RC drilling	0.3	500	250	Topsoil replacement and grassland reinstatement
VS2	RC drilling	0.3	500	430	Rehabilitation and re-establishment of forestry area
SS	Conventional shaft sinking	1.2	1,500	3,100	More extensive restoration of agricultural land due to larger surface working area
	Raise boring	0.5	1,200	3,100	Restoration of agricultural land
	Shaft sinking with muck pass	0.9	1,500	3,100	Similar to that for conventional shaft sinking without a muck pass

PRACTICAL DESIGN & CONSTRUCTION CONSIDERATIONS

Ground Support Strategy & Final Lining

Ground support and final lining requirements were considered at a preliminary level in relation to anticipated ground conditions, shaft excavation method, and long-term function of each shaft.

For the ventilation shafts, where RC drilling is adopted as the reference method, primary stabilisation during excavation will be provided by the drilling fluid/mud column, and by the steel casing to be installed as the final lining.

The surge shaft, as a permanent hydraulic structure, requires installation of permanent ground support (bolts, mesh and shotcrete) during/after shaft excavation followed by installation of a permanent final lining over its full depth irrespective of the construction method adopted. The permanent ground support in the shaft sidewalls, will be designed to carry all rock loads with an adequate Factor of Safety, while the cast-in-situ reinforced concrete final lining, approximately 500 mm thick, will be designed to resist external groundwater pressures under operational conditions. The sidewall support design, and final lining design including reinforcement, as well as shaft-tunnel intersection layout and detailing, will be developed during detailed design.

In the case of a raise bored surge shaft, no support can be installed during raise boring and the permanent ground support required (bolts, mesh and shotcrete), will have to be installed working top-down after raise boring work has been completed.

In conventional shaft sinking with/without a muck pass, permanent ground support (bolts, mesh and shotcrete) will be installed progressively as shaft excavation advances. This is particularly advantageous within the highly jointed/fractured dolerite, and in the weak fractured shale, where more active ground control will be required at an early stage in the excavation and support cycle. In practice, the larger support demand in the surge shaft is one of the factors favouring conventional shaft sinking as the more robust baseline method.

Groundwater Management
Groundwater management requirements will vary according to the selected shaft sinking method, but in all cases water handling, temporary storage, and water quality control will form part of the construction planning.

For RC drilling, the primary requirement is management of the drilling fluid circuit, including settlement capacity for cuttings removal, recirculation of clarified water, and disposal of dried solids.

For conventional shaft sinking without a muck pass, groundwater inflows will be managed by collection in shaft sumps and pumping to surface, with temporary settlement and treatment where required. For raise boring and for shaft sinking with a muck pass, water inflows will be handled at shaft bottom level.

In the surge shaft, areas of groundwater inflow (i.e., wet areas, water-bearing joints and fissures, more permeable strata) will require local treatment and / or installation of water control measures, during excavation and support for conventional shaft sinking, or post-excavation during installation of ground support in a raise bored shaft. Such measures may include installation of cuspated drainage sheets before meshing and shotcreting, drilling of drainage holes, installation of drain pipes, consolidation grouting, etc., as may be appropriate.

Groundwater quality also requires consideration. The project investigations indicate the potential for acidic water and elevated dissolved metals associated with pyritic shale, particularly within the Pietermaritzburg Formation. Temporary treatment measures such as neutralisation and settlement may therefore be required prior to discharge, subject to the applicable Water Use Licence conditions

LOGISTICAL & ACCESS CONSIDERATIONS

Logistical requirements differ materially between the shaft construction methods and are therefore relevant to the overall constructability assessment.

For the ventilation shafts, RC drilling offers the simplest mobilisation and the smallest surface footprint. The method requires a drill rig, mud pumps, surface tanks / sumps, and associated service infrastructure, with comparatively limited site establishment requirements. This is advantageous at the relatively constrained ventilation shaft construction sites and reduces temporary disturbance and associated rehabilitation requirements.

For the surge shaft, raise boring requires mobilisation of specialist large-capacity equipment, with higher demands in terms of transportation logistics, longer lead times, and more extensive site establishment than the ventilation shaft works. Conventional shaft sinking, while based on equipment and skills that are more readily available locally, requires the largest surface infrastructure footprint owing to the need for a headgear, winding arrangements, ventilation, mucking systems, and associated temporary works. It also results in the longest site establishment period of the considered methods.

Site access at all three shaft locations is generally feasible using existing farm or forestry roads, although local upgrades along access routes will be required. These access requirements are of particular importance at the surge shaft because road works and site establishment must be planned in accordance with the blue swallow environmental constraints. Temporary power, water supply, and communications will also be required at each site, but no exceptional service constraints have been identified in this regard.

Overall, the logistical and access considerations reinforce the broader method comparison: RC drilling is well suited to the ventilation shafts because of its limited footprint and relatively simple mobilisation, while surge shaft construction involves a trade-off between the smaller operational footprint of raise boring and the greater flexibility, but larger infrastructure demand, associated with conventional shaft sinking.

CONCLUSIONS & RECOMMENDATIONS

The assessment confirms that shaft construction method selection for uMWP-1 is governed by a combination of shaft geometry, ground behaviour, groundwater conditions, support demand, and programme constraints, rather than by depth alone.

1. Scale is the primary discriminator in method selection

   For the 1.5 m diameter ventilation shafts, RC drilling provides the most favourable balance of speed, safety, limited surface footprint, and programme certainty. For the surge shaft with 6.0 m excavated diameter, larger-diameter shaft excavation methods are required, and the selection becomes a trade-off in terms of geotechnical flexibility and overall programme efficiency.

2. Ground behaviour is a critical design input

   The geotechnical evaluation shows that structurally controlled instability is relevant to all three shafts, while the dominant local challenges differ between them. Shaft stability at VS2 will be governed by a short faulted and water-bearing interval at approximately 117-123 m depth, whereas the surge shaft is governed by a more extended weak fractured shale interval between approximately 56 m and 73 m depth as well as a highly jointed / fractured interval in dolerite. These differences directly influence both support demand and method suitability.

3. Programme constraints are particularly significant for the surge shaft

   The blue swallow environmental restriction, which limits construction to a six-month annual working window at the Baynesfield outlet, places strong emphasis on programme efficiency for the surge shaft. However, the requirement for prior shaft-base access in a raise boring arrangement, and shaft intersections with weak and / or highly jointed ground, means that conventional shaft sinking provides the more robust shaft excavation method, while raise boring remains a conditional alternative where access, sequencing, and weak-ground risks can be satisfactorily managed within the overall project schedule.

4. Groundwater and weak / poor ground intersections remain key considerations

   Groundwater will require appropriate management during construction. In the surge shaft, the extended weak interval is expected to require more sidewall support.

Overall, based on the evaluation completed to date, the preferred construction methods are shaft-specific and reflect the interaction between shaft geometry, geology, groundwater, support demand, and project constraints.

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REFERENCE

American Society of Civil Engineers, 2022. Geotechnical Baseline Reports: Suggested Guidelines. 3rd ed. Reston: s.n.

Barton, N., Lien, R. & Lunde, J., 1974. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, pp. 189-236.

Bieniawski, Z., 1989. Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering.. New York: Wiley-Interscience.

Boniface, A., 2000. Tunnel Boring Machine Performance in Basalts of the Lesotho Formation. 15(4), pp. 391-397.

GKP Joint Venture, 2026. Geotechnical Baseline Report: uMWP-1 Water Conveyance Infrastructure. Report No. 19041-R-1193-0027 (Rev 0), Johannesburg.: GIBB Knight Piésold.

ITACET Working Group 23, 2019. Contractual Framework for Tunnelling. Lausanne: International Tunnelling Association (ITACET).

Lesotho Highlands Development Authority, 2004. Lesotho Highlands Water Project Phase 1B - Mohale Tunnel As-Built Report, Maseru.: Lesotho Highlands Development Authority.

Rocscience Inc., 2026. Dips (Version 9.002), Toronto: Rocscience Inc..

Rocscience Inc., 2026. UnWedge (v5.019), Toronto: Rocscience Inc..

Weir, R. & Oudshoorn, F., 2020. Generic Environmental Management Programme (EMPr) for the LandCare Programme , s.l.: Muvuledzi Consulting .

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Bridget Rodrigues is a Rock Mechanics Engineer with over nine years of experience in the mining industry. She holds a BSc (Hons) in Applied Science (Mining) from the University of Pretoria, South Africa, and has worked in both operational geotechnical roles (South Africa) and consulting environments (UK and South Africa).Bridget has extensive experience in both underground and open pit rock mechanics. She has contributed to a wide range of technical and multi-disciplinary mining projects, from early-stage scoping studies through to definitive feasibility studies. Her background includes due diligence assignments, geotechnical audits, and support to operating mines across several commodities and mining methods.

She has worked on projects across Southern Africa, Canada, the Middle East, South America, and Europe, gaining exposure to diverse geological environments and rock mass conditions. Her experience spans weak, highly weathered mudstones through to strong, competent norites of the Bushveld Complex. Bridget's technical strengths include site investigation planning and execution, geotechnical logging and interpretation, empirical and numerical analysis, ground support design, and the development of geotechnical models for both open pit and underground applications.

Over the past year, Bridget has been an integral member of the geotechnical design team for the uMkhomazi Water Project Phase 1 (uMWP-1), contributing to geotechnical investigation planning, logging oversight, analysis, and geotechnical characterisation for deep tunnel and shaft infrastructure.

She has substantial experience in geotechnical interpretation, limit equilibrium and stability assessments, and the design and of slopes, shafts, and underground excavations. Bridget is also experienced in preparing design reports, technical specifications, and tender documentation for mining projects.

Investigating the effect of aggregate type on the strength and energy absorption of shotcrete in Block Cave Mining

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In mining and tunnelling environments, large excavations are subjected to increasing rock stresses, making shotcrete performance critical for effective and sustainable ground support. Shotcrete stabilises excavations by controlling rock deformation and distributing loads, thereby reducing localised stress concentrations. Its performance, however, is strongly influenced by mix design, aggregate mineralogy, cement type, and additives such as fibres. This paper investigates the decline in mechanical performance of fibre-reinforced shotcrete at Palabora Mining Company following the introduction of mica-rich aggregates during the transition from a surface-based mixing plant to a newly commissioned underground batch plant. Laboratory testing was conducted to evaluate the uniaxial compressive strength (UCS) and energy absorption performance of shotcrete produced using mica-rich aggregates and dolerite aggregates. Specimens were cured and tested at seven and 28 days to assess early-age and standard design strength development. The results indicate consistently poor performance of shotcrete incorporating mica-rich aggregates, with 28-day UCS values remaining below 40 MPa, failing to meet the mine's specified requirement of 45 MPa. The reduced performance was attributed to increased water demand and weakened cement–aggregate bonding, associated with the high phlogopite mica content. In contrast, shotcrete produced using dolerite aggregates consistently exceeded the required UCS at both curing ages and demonstrated superior energy absorption performance with the same fibre content. Although this investigation was conducted in a block cave mining environment, the findings are directly applicable to tunnelling operations, where reliable shotcrete performance is essential for long-term excavation stability.

Keywords: Shotcrete, Aggregate type, Energy absorption, UCS, Block Cave Mining

INTRODUCTION

In block cave mining, shotcrete is an essential part of the ground support system for the long-term stability and integrity of the excavations. This type of concrete is sprayed at high velocity over surfaces to create a barrier of reinforcement that stabilises the excavations and prevents them from fracturing and collapsing. The performance of shotcrete is significantly influenced by the mix design, which is composed of cement, admixtures, and aggregates (such as river sand and/or crushed rocks). To guarantee that the shotcrete has the required strength, durability, and energy absorption capabilities, the mix design must be thoroughly designed and optimised. This paper is based on case study research at Palabora block cave mining operations.

Palabora Mining Company (PMC) is a large-scale mine and requires significant volumes of shotcrete for ground support. With the Lift II cave extension project situated at 1650 m below surface, that is 450 m below the existing Lift I cave, the surface mixing plant became a bottleneck to the shotcrete demands.

To mitigate the logistic challenges of having a shotcrete mixing plant on the surface, the mine constructed an underground mixing plant at Lift I with a similar set-up and operation to the existing surface plant. In July 2021, the construction of the underground mixing plant was successfully completed and the transition to underground mixing plant operations was phased in, replacing the surface batch/mixing plant to alleviate operational constraints and meet the growing demand for shotcrete. The surface batch plant had shaft constraints, most notably the need to move mixer trucks (agitation trucks) from underground to the surface for batching before returning them underground. This procedure was inefficient, resulting in production delays and lots of disruptions on the vertical shaft operation. The development of an underground batch plant was to simplify operations by eliminating the need for this time-consuming transportation, enhancing production efficiency and satisfying the strong demand for shotcrete. However, the transition was not smooth and created unexpected challenges in the quality of shotcrete production due to the supplier of aggregates (both river sand and crushed rock) being changed without testing aggregate compatibility to the original design. A significant performance drop was noted and concerns with the shotcrete were raised shortly after the underground batch facility commenced operations. The shotcrete developed lower uniaxial compressive strength (UCS) and energy absorption capacity, as well as a reduction in open time (flow retention) both of which are crucial for providing appropriate workability and required ground support for the conditions (Yun *et al.,* 2021). These deficiencies compromised the long-term stability of the tunnels and integrity, posing a significant risk to mining operations and safety.

Research conducted by Santhosh *et al.,* (2021) highlighted the importance of maintaining constant shotcrete quality during production transitions, with the mechanical properties of shotcrete greatly affected by variations in the type of aggregate, moisture content, and batching procedures. Menu *et al.,* (2022) conducted an experimental study that illustrated how modifications in aggregate composition affected shotcrete performance. It highlighted the importance of conducting comprehensive testing and quality control while making changes to the mix design. A substantial body of literature also exists (Chen *et al.,* 2023; Duarte *et al.,* 2019; Nobre *et al.,* 2020) documenting the effect of coarse recycled aggregate, fine and lightweight aggregate on the performance of shotcrete.

While the negative effects of mica are well-known in general concrete technology, this paper focuses on the specific performance of shotcrete under the high-stress conditions of deep-level mining at the PMC Lift II project. Meanwhile, shotcrete is a highly effective material for stabilising underground excavations, offering instant support and enhancing long-term stability (Sun *et al.,* 2020). Various factors affect shotcrete quality, such as the type and quality of aggregates utilised, the ratio of cement to water, and the inclusion of admixtures. Bernard (2020) emphasised the need to optimise the shotcrete mix design to achieve the desired mechanical properties and ensure its effectiveness in harsh underground environments. This paper specifically addresses how the combination of mica-rich aggregate and high clay content affects these mechanical properties in a deep-mining context.

Problem statement

Shotcrete from the underground batch/mixing plant exhibited substantial quality issues from July 2021 through December 2021. The shotcrete exhibited values significantly lower than expected for both energy absorption, UCS and open time. This posed a serious problem to the shotcrete's capability to provide adequate ground support performance and long-term tunnel stability. The decline of the compressive strength of the shotcrete is depicted in Figure 1. The required UCS of the shotcrete at seven days is 25 MPa, and 45 MPa at 28 days, as indicated by the two dashed lines.

Figure 1. UCS cube results for surface batch plant standard shotcrete from 2018 to 2020 and mica and clay-rich aggregate shotcrete from 2021.

An investigation revealed that the type of aggregate used in the underground batch plant was different from that used in the surface batch plant. The original mix design was designed for crushed dolerite waste rock sourced directly from the mine and river sand with low clay content. For the underground batch plant, an alternative dyke was sourced from a nearby mine due to a breakdown of the onsite batch plant crusher and a change in the river sand supplier. This dolerite was discovered to be high in phlogopite mica, which influenced the overall performance of the shotcrete. Furthermore, the river sand used in the mix design at the underground batch plant was finer and contained a higher clay percentage than the original mix design. This resulted in an increased water demand of the mixture, compromising the open time, strength, and energy absorption capacity of the shotcrete. Since the mixture was blended at the underground batch plant, the individual effects of the aggregates could not be isolated within the production environment. As a result, the study evaluated the performance of both aggregate types rather than separately

This paper examines the challenges encountered following the relocation of the batch plant underground, the corrective processes implemented to address shotcrete quality concerns, and the subsequent investigation into their root causes. The investigation focused primarily on the influence of variations in aggregate type and other mix design constituents on shotcrete performance.

METHODS

Initial Investigation

An initial investigation was conducted to identify the root causes of poor shotcrete performance following the commissioning of the underground batch plant. The investigation began with a desktop study in which the original shotcrete mix design used at the surface batch plant was compared with the mix design implemented at the underground batch plant to identify any discrepancies.

This was followed by a detailed assessment of all mix constituents, with particular emphasis on aggregate sources. The original mix design utilised crushed dolerite waste rock from the mine, combined with low clay content river sand. Due to the breakdown of the surface crusher, alternative aggregates were sourced from an external supplier. Samples of both the original onsite dolerite crusher sand and the externally supplied crusher sand were collected and examined to evaluate mineralogical composition and suitability for shotcrete production.

In addition, the quality of river sand was assessed. Grain size distribution analyses were conducted to compare the original river sand with the newly sourced material. Conventional laboratory methods were used to determine clay content, with particular attention given to its potential influence on water demand and the water-to-cement (W/C) ratio of the mix.

Laboratory Testing

A comprehensive laboratory testing programme was implemented to evaluate the effect of changes in aggregate type and river sand quality on shotcrete performance. All constituents were mixed in a batching plant under constant rotation to ensure homogeneity. The batching process at the underground batch plant was systematically evaluated to assess calibration, accuracy, and consistency. The automated dosing system was tested to verify that the correct quantities of water, cement, and chemical admixtures (including superplasticiser and retarder) were being dispensed in accordance with the specified mix design.

Sample preparation was carried out daily over a monthly period in accordance with ASTM C1140 standards. Shotcrete samples representing both the original mix design (using site aggregates) and the modified mix design (using externally sourced aggregates) were prepared for testing. UCS tests (Figure 2B) were conducted on cube specimens cured under controlled laboratory conditions. UCS testing was performed at curing ages of seven and 28 days to evaluate strength development over time.

In addition to compressive strength testing, the energy absorption capacity of the shotcrete panels was assessed using flexural testing facilities (Figure 2A). These tests were conducted under loading conditions representative of underground mining environments. Compressive strength and energy absorption testing were performed in accordance with ASTM C109 and ASTM C1550 standards, respectively.

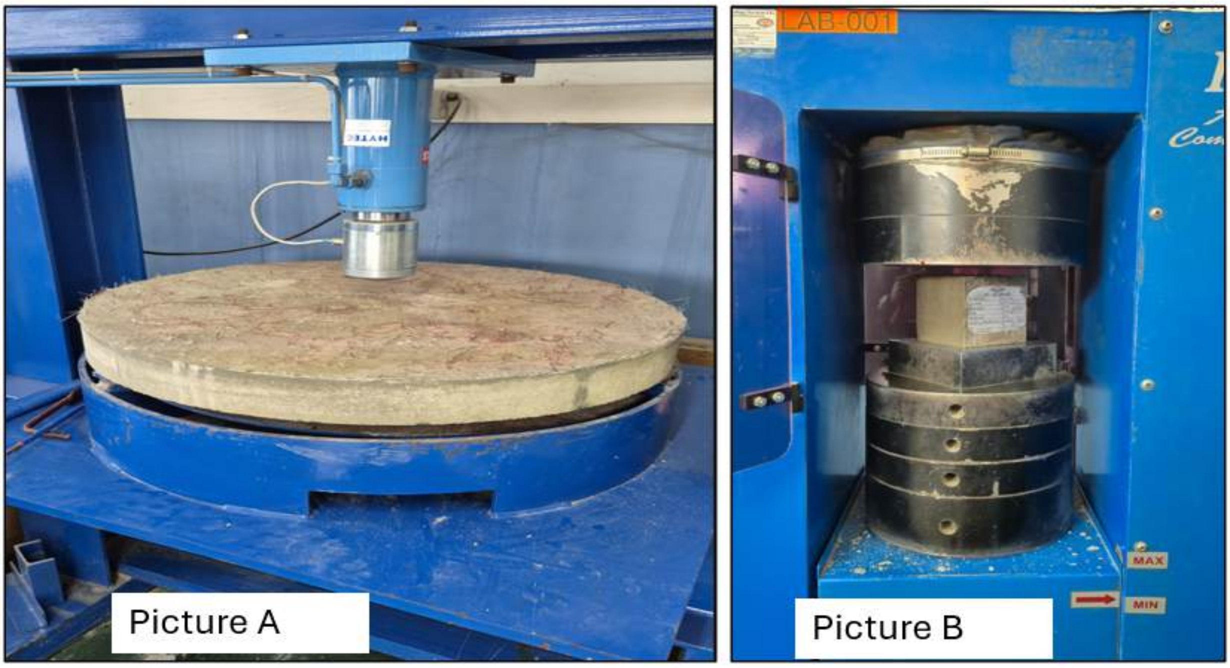

Figure 2: Picture A illustrates the energy absorption round determinate panel sample test, and picture B illustrates the cube samples test for UCS.

RESULTS AND DISCUSSION

This section presents the shotcrete test results for both mix designs, including UCS results at seven and 28 days of curing and 28-day energy absorption obtained from round determinate panel tests. The results cover three distinct periods: prior to the change in aggregates, during the use of mica-rich crusher sand and high clay content river sand, and after the intervention in which clean dolerite and low clay content aggregates were adopted

Evolution of compressive strength of shotcrete over time

As shown in Figure 3, the desktop investigation indicated that the UCS of the standard shotcrete from January to June 2021 complied with the specified requirements at both seven and 28 days. A sudden decline in UCS was observed in July 2021. This reduction in strength was attributed to inadequate commissioning of the new underground batch plant. The decline was further associated with the introduction of new aggregates, namely mica-rich crusher sand and high-clay-content river sand, into the original mix design. These changes were implemented without following established procedures or consulting key stakeholders, including the geotechnical department. Consequently, the UCS values showed fluctuations over the monitoring period, with noticeable variability between September 2021 and February 2022.. The laboratory results showed that the newly sourced external crusher sand was rich in mica, while the river sand had a high clay content, both of which negatively affected the strength of the shotcrete. The new aggregates resulted in increased water dosage used in the mix (more than the standard W/C of 0.45-0.5), resulting in unsatisfactory shotcrete performance. Additionally, this led to an early setting of the shotcrete. Studies (Mshali and Visser, 2012; Munoz *et al.*, 2010) showed that a little bit of mica (not more than 2%) is good for the mechanical performance of shotcrete or mortar. A small quantity of mica is reported to reduce the void ratio of shotcrete by filling the voids in the aggregate. As a result, the strength gain of shotcrete is achieved. However, an increase in mica content is reported to have a negative impact on the strength of shotcrete. This is because a high content of mica increases the porosity of shotcrete, and as a result, increases water absorption (Nehdi, 2014). Additionally, the mica flakes hinder the bond between cement and aggregate, thus affecting the hardening process. Similarly, fines and high clay content in river sand reduced the strength of the shotcrete (Al-harthy *et al.*, 2007); moreover, excessive water content in fine aggregate forms a water film. The presence of fines, mica, and clay in the aggregate increases the water demand of the shotcrete mix, which initially reduces workability at a given water–binder ratio. To achieve a workable, homogeneous mixture, operators add additional water. This compensates for the reduced flowability, but also increases the effective water–binder ratio. As a result, the hardened shotcrete exhibits lower compressive strength, reduced toughness, and shrinkage-induced microcracking(Chen *et al.*, 2023). Excessive clay content and mica-rich aggregates led to reduced and more variable strength, poorer handling characteristics and compromised long-term performance.

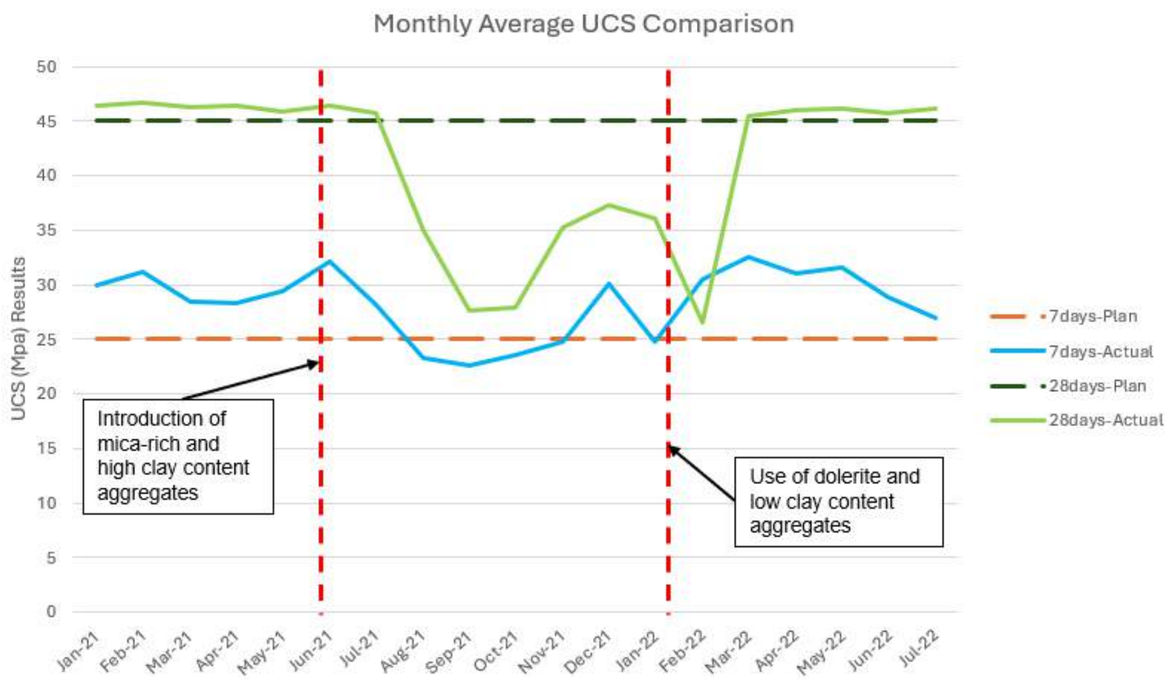

Figure 3. Illustrates the initial drop of the shotcrete UCS performance and fluctuations over time.

Figure 4 demonstrates the monthly average UCS results of the improved shotcrete mix design over time. The adopted mix design shows improved shotcrete performance that complies with the required standards and specifications for both seven- and 28-days results. As depicted, a gradual increase in strength was observed from March 2022 onwards. While minor discrepancies in strength were noted among the samples, it is important to note that the workability and open time met the mine specification. Due to logistical constraints and the dynamics of the Lift II project, which affect the availability of shotcrete placement sites, the mix design was required to maintain an open time of at least eight hours. The revised mix design was therefore developed not only to achieve the required UCS and energy absorption performance, but also to ensure adequate workability and extended open time under these operational conditions.

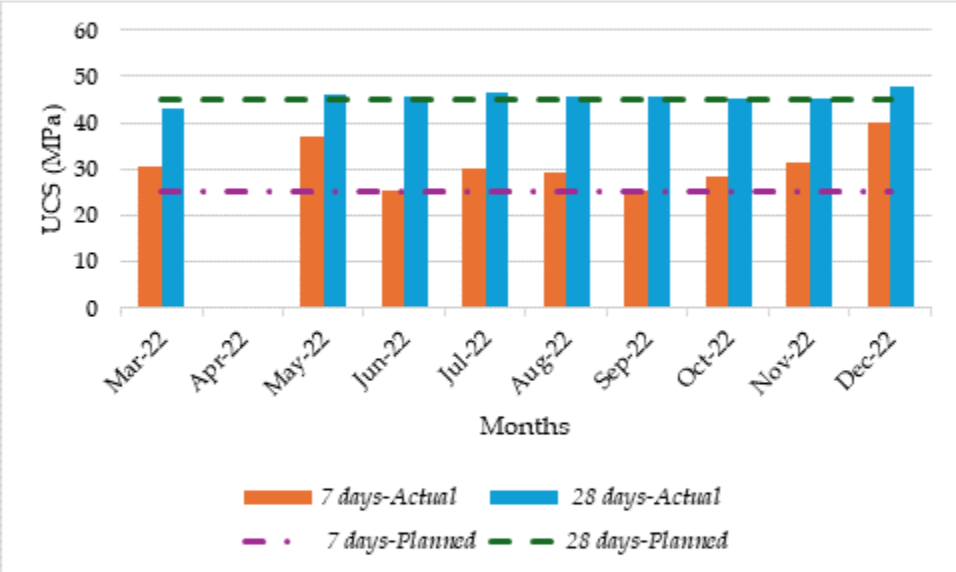

Figure 4. Improved shotcrete UCS results over time post-investigation and interventions.

Energy absorption comparison of both mix designs

The energy absorption of shotcrete refers to its ability to absorb energy from external/dynamic loading, such as rock bursts and seismic events, thereby preventing rock failure (Khosh and Atapour, 2024). The load-displacement curve presented in Figure 5 depicts the results from the flexural tests. The area under the curve from 0 – 40 mm denotes the energy absorption of shotcrete. While this value can be calculated from the curve, the testing apparatus automatically generates the energy absorption graph through direct measurement, presented by the energy-displacement (blue line) graph. The required energy absorption of shotcrete by the mine (PMC) is 900 J at 28 days, as per the EFNARC standards. The energy absorption value from the ASTM panel test graph at 40 mm deflection is multiplied by 2.5 to convert to the EFNARC standard (Morton *et al,* 2009). Figure 5 shows that the maximum load required to induce a crack was 25 kN. At this point (at 2 mm deflection), a cracking sound can be heard, but there were no cracks visible on the sample. Moreover, the curve also reveals that the maximum energy that the shotcrete can absorb is 1500 J at a displacement of 40 mm. In alignment with the findings of Cengiz and Turanli (2004) and Jeng *et al.*, (2002), energy absorption is directly correlated with shotcrete toughness; consequently, higher energy absorption values signify increased toughness of shotcrete.

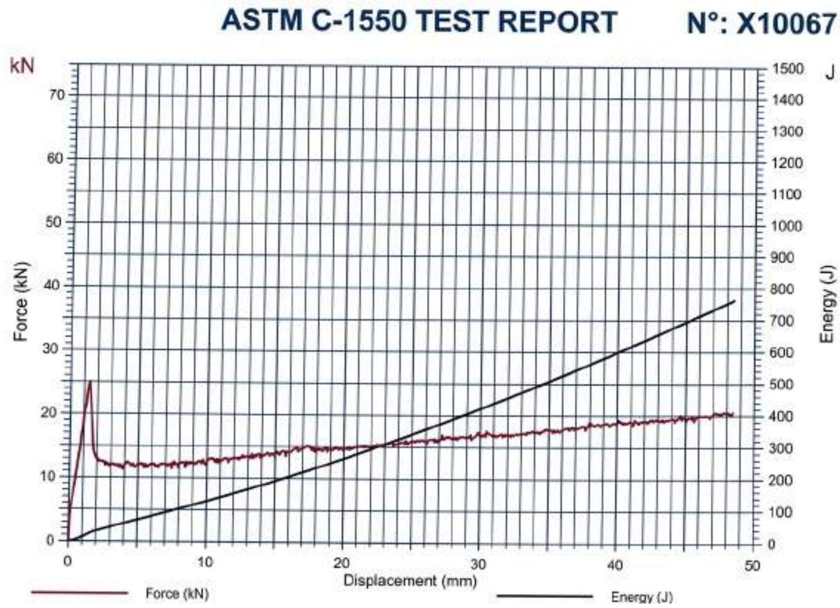

Figure 5. Load-displacement curve for improved shotcrete.

Figure 6 describes the energy absorption of the mica-rich, high-clay shotcrete mix at 28 days. The minimum amount of energy required to initiate the first crack was found to be approximately 200 J, with a maximum load capacity of 210 J read off directly from the graph or 420 J if converted to EFNARC standards. This is below the 900 J project requirement; therefore, the impact of the mica and clay properties within the aggregate is evident. Phlogopite mica consists of smooth, platy particles that do not bond well with the cement paste. These flat surfaces create internal planes of weakness and increase porosity, preventing the shotcrete from reaching high energy-absorption levels. (Norvell *et al.*, 2007).

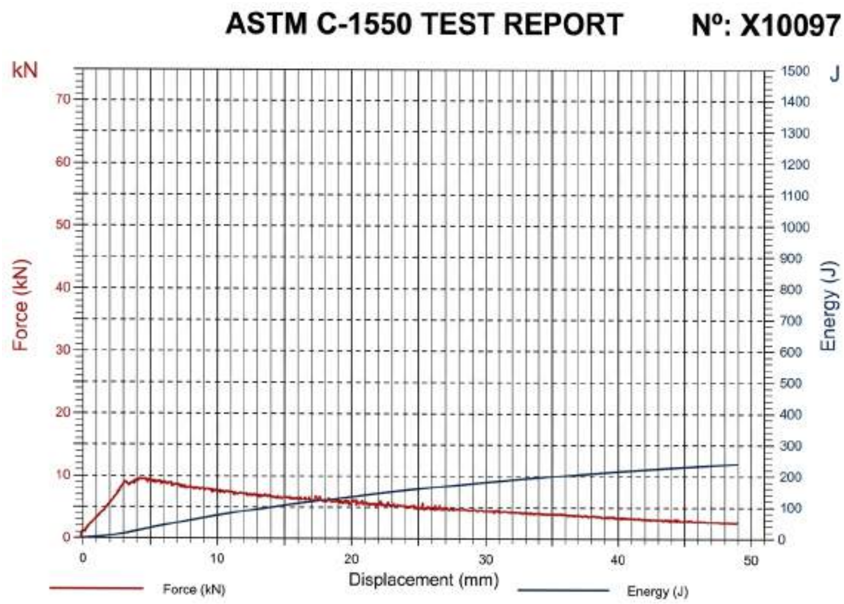

Figure 6. Load-displacement curve for mica-rich and high clay content shotcrete mix.

CONCLUSION

The effect of mica-rich and high clay content aggregate on the performance of shotcrete has been investigated. The study compared the impact of the different types of aggregates on the mix design's performance. The first/initial mix contained crushed dolerite (with a very low quantity of mica/uncontaminated) and well-graded low clay content river sand (5 mm), while the second mix consisted of mica-rich dyke from a neighbouring mine and fine-grained high clay content river sand. The main conclusions obtained from this study are as follows:

- A low mica content in aggregate may have minimal impact on shotcrete performance. However, higher mica content increases the water demand of the mix due to the mineral's platy, layered structure, which reduces workability unless additional water or admixture is added. When extra water is added to compensate for the poor workability, the resulting increase in the effective w/c ratio leads to reduced strength in the hardened shotcrete. Moreover, the phlogopite-rich and high-clay aggregates are unsuitable for the PMC Lift II project, as the resulting shotcrete critically failed, absorbing only 210 J against the required 900 J energy target.
- Mica-rich aggregate reduces the energy absorption of shotcrete, which also represents its toughness. Consequently, low energy absorption means weak shotcrete, increasing the likelihood of cracking and compromising tunnel stability.
- Like mica, excess fines and high clay content in sand increase the water demand of the mix. This may make the mixture appear workable initially but effectively raises the w/c ratio and potentially reduces strength.
- Changing any of the shotcrete mix design constituents without following due process not only affects the mix design performance, but it also affects the operational schedule and has high-cost implications on the business.
- Excess water added to the shotcrete mix due to high water demand reduced the strength development of the shotcrete.
- While both the phlogopite-mica-rich dolerite and clay-rich sand are known to adversely influence workability and water demand, the sand may additionally promote shrinkage-related cracking and affect permeability. This limitation is acknowledged, and future controlled laboratory testing is recommended to independently quantify the influence of each aggregate on the mechanical properties of shotcrete.

REFERENCES

Al-Harthy, A. S., Halim, M. A., Taha, R., and Al-Jabri, K. S., 2007. The properties of concrete made with fine dune sand. Construction and Building Materials, 21 (8), 1803-1808.

Cengiz, O., and Turanli, L., 2004. Comparative evaluation of steel mesh, steel fibre and high-performance polypropylene fibre reinforced shotcrete in panel test. Cement and Concrete Research, 34 (8), 1357-1364

Bernard, E.S. ed., 2020. Shotcrete: Engineering Developments. CRC Press.

Chen, L., Sun, J., Liu, G., and Li, C., 2023. Effect of fine aggregate on fluidity and mechanical properties of wet shotcrete. Advances in Cement Research, 35(7), 317-332.

Duarte, G., Bravo, M., De Brito, J., and Nobre, J., 2019. Mechanical performance of shotcrete produced with recycled coarse aggregates from concrete. Construction and Building Materials, 210, 696-708.

Jeng, F., Lin, M., and Yuan, S., 2002. Performance of toughness indices for steel fiber reinforced shotcrete. Tunnelling and Underground Space Technology, 17(1), 69-82.

Khosh, B., and Atapour, H., 2024. Assessment of mechanical behavior of sprayed concrete reinforced with waste tire textile fibers. Scientific Reports, 14, 8873.

Mshali, M. R., and Visser, A. T., 2012. Influence of mica on unconfined compressive strength of a cement-treated weathered granite gravel. Journal of the South African Institute of Civil Engineering, 54 (2), 71 – 77

Menu, B., Beaudet, A.P., Jolin, M. and Bissonnette, B., 2022. Experimental study on the effect of key mix design parameters on shrinkage and cracking resistance of dry-mix shotcrete. Construction and Building Materials, 320, p.126216.

Morton, E.C., Villaescusa, E. and Thompson, A.G., 2009. Determination of energy absorption capabilities of large-scale shotcrete panels.

Munoz, J.F., Gullerud, K.J., Cramer, S.M., Tejedor, M.I. and Anderson, M.A., 2010. Effects of coarse aggregate coatings on concrete performance. Journal of Materials in Civil Engineering, 22(1), pp.96-103.

Nobre, J., Bravo, M., de Brito, J., and Duarte, G., 2020. Durability performance of dry-mix shotcrete produced with coarse recycled concrete aggregates. Journal of Building Engineering, 29, 101135.

Norvell, J., Stewart, J., Juenger, M. and Fowler, D. 2007. Influence of clays and clay-sized particles on concrete performance. Journal of Materials in Civil Engineering, 19(12), 1053-1059

Nehdi, M.L., 2014. Clay in cement-based materials: Critical overview of state-of-the-art. Construction and Building Materials, 51, 372-382.

Santhosh, K.G., Subhani, S.M. and Bahurudeen, A., 2021. Cleaner production of concrete by using industrial by-products as fine aggregate: A sustainable solution to excessive river sand mining. Journal of Building Engineering, 42, p.102415

Sun, W., Shengyou, Z., Feng, X. and Hou, K., 2020. Analysis on the influence factor of low-strength wet shotcrete in frigid mining area. Archives of Mining Sciences, 285-298.

Yun, K. K., Choi, S., Ha, T., Kim, S. K., Hossain, M. S., and Han, S., 2020. Long-term compressive strength development of steel fiber shotcrete from cores based on accelerator types at tunnel site. Materials, 14(3), p. 580.

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Mr Mtshali Thokozani Sidwell is a highly passionate mining professional with experience in variety of mining methods from underground deep level gold mining, trackless operations, underground conventional gold mining, open pit and block caving (undercutting and draw bell development) at a copper mine. He is currently employed at Palabora Mining Company (PMC) as a Chief Rock Engineer tasked with the responsibility of the rock engineering duties for the whole mine starting from surface to underground mine.

What has the mining industry done for underground civil construction and what is the civil construction industry doing

D. Lees

David Lees and Associates, Australia

What has the mining industry done for underground civil construction and what is the civil construction industry doing in return? The first answer to this question is easy – the mining industry has trained and educated young mining engineers who have then found employment in civil tunnelling projects. What makes a mining engineer such a good prospect for civil tunnelling work? Firstly, they know the underground environment, but not only do they know and understand the underground environment but because their training and education is so well rounded in electrical and mechanical engineering, structural engineering, geology and geotechnical engineering, they can put their minds to all the everyday challenges that the fields of underground excavation present.

A BRIEF HISTORY OF UNDERGROUND EXCAVATION

So, the question is then what came first – underground mining or underground excavation for civil works?

The oldest known mine on archaeological record is the 'Lion Cave' in Swaziland, which radiocarbon dating shows to be about 43,000 years old. At this site Paleolithic humans mined hematite to make the red pigment ochre.

We also know that Neolithic man mined for flints in areas such as Norfolk in England between about 3000 to 1900 BC (Russel, 2000). Flint was much in demand for making polished stone axes in the Neolithic period. Grimes Graves extends over an area of some 37 ha and consists of at least 433 shafts dug into the natural chalk to reach seams of flint. The largest shafts are more than 14 m deep and 12 m in diameter at the surface. It has been calculated that more than 2000 tonnes of chalk had to be removed from the larger shafts, taking 20 men around five months, before stone of sufficient quality was reached.

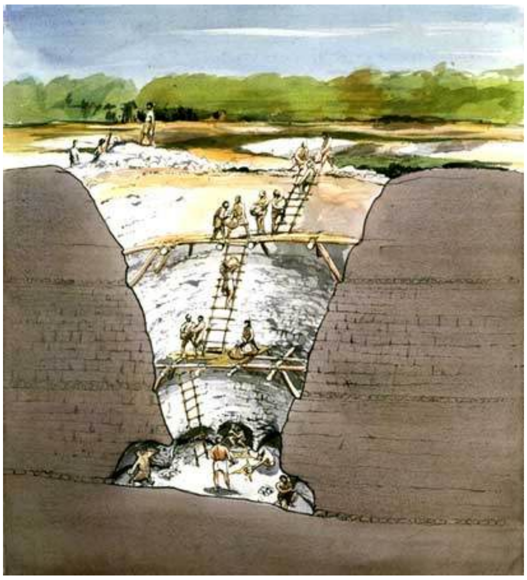

Figure 1: Grimes Graves flint mine.

In harsh climates of the world, the underground became a natural refuge. The newly-discovered subterranean city beneath Nevşehir in Turkey is thought to date back 5000 years. The subterranean city includes caves, tunnels, hidden churches, and escape galleries honeycombed beneath the surface.

Figure 2: Cappadocia subterranean city.

With one hundred square miles and more than 200 underground villages and tunnel towns complete with hidden passages, secret rooms and ancient temples and a remarkably storied history of each new civilisation building on the work make Cappadocia one of the world's most striking and largest cave-dwelling regions of the world.

But the need for man for natural resources such as coal, copper, tin and iron as well as man's lust for gold and precious jewels meant that most of the advances in understanding of underground construction were developed by the mining industry.

It was the Romans who developed large scale mining methods, especially the use of large volumes of water brought to the mine head by numerous aqueducts. The water was used for a variety of purposes, including removing overburden and rock debris, called hydraulic mining, as well as washing crushed ore and driving simple machinery.

The Romans used hydraulic mining methods on a large scale to prospect for the veins of ore, especially a now obsolete form of mining known as hushing. This method involved building numerous aqueducts to supply water to the mine head where it was stored in large reservoirs and tanks. When a full tank was opened, the flood of water sluiced away the overburden to expose the bedrock underneath. The rock was then worked upon by fire-setting to heat the rock, which would be quenched with a stream of water. The resulting thermal shock cracked the rock, enabling it to be easily removed.

Roman techniques were not limited to surface mining. They followed the ore veins underground once opencast mining was no longer feasible. At Dolaucothi they stoped out the veins, and drove adits through barren rock to drain the stopes. The same adits were also used to ventilate the workings - especially important when fire-setting was used. Ventilation was achieved by building fires at the bottom of shafts to draw air through the workings.

Romans also excavated beneath the water table and dewatered the mines using several kinds of machines, especially reverse overshot water-wheels. These were used extensively in the copper mines at Rio Tinto in Spain, where one sequence comprised 16 such wheels arranged in pairs, and lifting water about 24 m. They were worked as treadmills with labourers standing on the top slats. Many examples of such devices have been found in old Roman mines and some examples are now preserved in the British Museum.

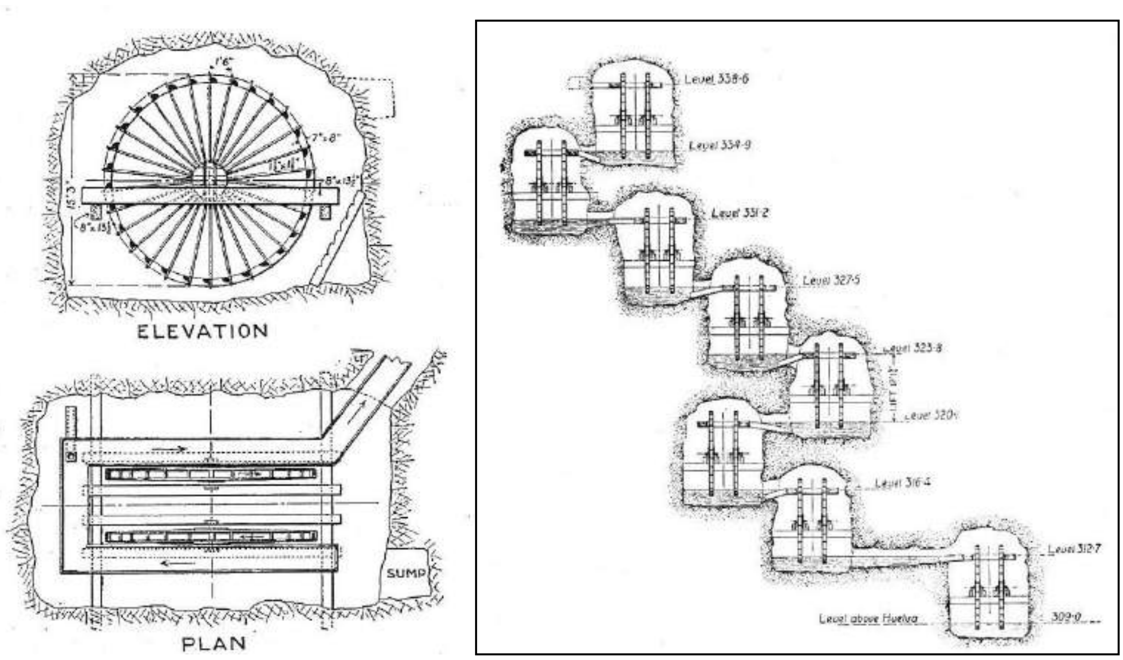

Figure 3: Drainage wheels from Rio Tinto mines (Boon and Williams, 1966).

Mining underwent dramatic development in medieval Europe with the extraction of copper and iron and other precious metals. Whilst initially many metals were obtained through open-pit mining, and ore primarily extracted from shallow depths, the increasing use of weapons and armour meant that continuing mining underground was inevitable.

One of the prime issues confronting medieval miners was the removal of water from mine shafts. As miners dug deeper to access new veins, flooding became a very real obstacle, but this was overcome with the invention of mechanical and animal-driven pumps. The use of water power in the form of water mills was extensive. The water mills were employed in crushing ore, raising ore from shafts, and ventilating galleries by powering giant bellows. Inventions like the arrastra were often used by the Spanish to pulverise ore after being mined where rocks were dragged around in a circle to pulverise ore. This device was powered by animals and used the same principles used for grain threshing.

Black powder was first used in mining in Selmecbánya, Kingdom of Hungary (now Banská Štiavnica, Slovakia) in 1627. Black powder allowed blasting of rock and earth to loosen and reveal ore veins.

Blasting was much faster than fire-setting and allowed the mining of previously impenetrable metals and ores.

The Asians had been using black powder since the 10th century for fireworks, and the Arabs stole it from the Asians and developed it for warfare. In the 13th century it was developed in Europe by Roger Bacon, but he did not get the credit for his invention as he didn't use it. In 1313 the monk Berthold Schwarz exploited its potential. Initially it was used for warfare projectiles; only later was its potential for breaking rock recognised. After some (unconfirmed) attempts in Italy and Saxony, documents show that in 1627, the Tyrolese miner Kaspar Weindl used black powder to blast a gallery at Schemnitz, in present-day Slovakia (Cressy, 2013). The rock was drilled by hand, one man holding the drill and hitting it, or two men (one holding the drill and turning it round after every blow, another hitting it with a heavy hammer). These holes, preferably narrow, were drilled to depths of 50-100 cm and then filled with a sufficient quantity of black powder, firmly pressed in. Wooden or (later) clay plugs were used to block the holes, through which fuses were then lit. During the 17th century this new technique was used all over the world but because of the very high cost of black powder and the extremely hard work of manually drilling the holes, blasting was mainly used only when very hard rock was worked.

Figure 4: Beating the bore - drilling by hand (photo JC Burrows: East Pool Mine Cornwall, UK 1890).

19th Century
With the Industrial Revolution came new developments in underground excavation with the need for faster and more efficient excavations in mines and the need for tunnelling with the development of railways. Steam pumping engines were used to remove water as shafts became deeper.

Rock drilling
Mechanised rock drilling developed from 1870 with the American Ingersoll and Rand rock drills using compressed air (Lees, 2001). These drills were of American origin and were a great achievement since they were designed with very few moving parts. But many new inventions were associated with new projects such as Mokean's rock drill for the St Gothard Tunnel. Mokean's rock drill included an

ingenious mechanism for automatic feed, but this feature was not possible to include in the lighter machines for ordinary mining and quarrying.

The Schram rock drill, a Swedish and German design, started an era of simplification. It had just four moving parts: a working piston which drove the borer, a slide valve, a slide rod, and a small piston which drove the working piston; all these were worked directly by the motor fluid. Mr. Schram was a mining engineer and, like his compatriots, realised an automatic feed was impractical and therefore did not include it in his design. The advantages of this design were quite obvious: the piston is perfectly free, the full fluid pressure is kept during the whole stroke, the friction loss is small and it has fewer moving parts, all of which are readily accessible. The whole construction of the machine is simple and strong.

Machine drilling spread quickly due to the much higher progress rates that were possible. With hand drilling typical progress of 18 inches a day was achieved (about 46 cm), whilst in 1948 at the Marievale Consolidated Mine in South Africa, 1227 feet (about 374 m) was achieved in 26 days with six 3 ½ inch Holman's drifters (that's a rate of over 47 feet or 14.3 m a day!).

These increases in penetration also meant more dust which meant an increase in silicosis or 'Miners Complaint', which killed many miners every year at a young age. The first place to tackle this problem was South Africa, where water was thrown from a puddle by a small tin. Then, in 1902, it became official that water should be used to dowse the dust and at this time Leyner designed a drill on which today's drills are still based. The steel was held loosely in a chuck attached to the cylinder itself and the piston reciprocated and struck the blunt end of the drill steel. The most important improvement was his method of introducing air down through the drill steel to keep the drill holes clear of rock. This raised a lot of dust, so he introduced water along the drill with the air; this innovation soon dominated the world market.

Blasting

In 1846 an Italian scientist named Ascano Sobrero thought of a new idea. He mixed nitric acid and glycerine together to see what would happen. The new substance nearly exploded in his face! Sobrero had discovered nitro-glycerine. In 1852 Alfred Nobel took up the task of making nitro-glycerine more stable so it could be used as a commercially and technically useful explosive. This proved to be very dangerous and resulted in the death of many people including his brother Emil. He soon found that mixing nitro-glycerine with silica would turn the liquid into a paste which could be shaped into rods of a size and form suitable for insertion into drilling holes. In 1867 he patented this material under the name of dynamite.

Two important developments in the history of explosives were the inventions of the safety fuse and the blasting cap. In 1831 William Bickford of England devised the safety fuse, originally a textile-wrapped cord with a black powder core, which for the first time enabled safe, accurately timed detonations.

In 1865 Nobel invented the blasting cap, providing the first safe and dependable means for detonating nitro-glycerine and thereby considerably expanding its use for industrial purposes. Electrical firing, first used successfully in the late 19th century, allows greater control over timing.

Ventilation

Explosions in coal mines from 'firedamp'– a toxic mixture of methane and air – caused many disasters in the 19th century. The Tyneside coal mines in England in particular had the deadly combination of bituminous coal contaminated with pyrites, and a great number of lives were lost in accidents due to firedamp explosions, including 102 dead at Wallsend in 1835. The miners dealt with it by piping it to the outside. A continuous flame was produced at Whitehaven some time before 1733, described by Holland (1841) as being "a yard wide and two yards long."

In 1815 both George Stevenson (the father of modern railways) and Sir Humphrey Davey developed miner's safety lamps. Both were based on slightly different principles. The Geordie Lamp by George Stevenson relied on the flow of air through a narrow chimney. Stevenson conceived that if the only way air could get to the flame was restricted (a baseplate pierced by a number of small-bore brass tubes was the usual way of doing this) and the lamp body above the flame lengthened, then the same amount of air could get to the flame, but would pass through the flow restriction at a velocity higher than the velocity of the flame in a mixture of firedamp (mostly methane) and air. This, then, prevented an explosive back blast that might light the surrounding air.

The Davey lamp developed by Sir Humphrey Davey was based on a series of gauzes. The lamp consists of a wick lamp with the flame enclosed inside a mesh screen. The screen acts as a flame arrestor; air (and any firedamp present) can pass through the mesh freely enough to support combustion, but the holes are too fine to allow a flame to propagate through them and ignite any firedamp outside the mesh. The lamp also provided a test for the presence of gases. If flammable gas mixtures were present, the flame of the Davy lamp burned higher with a blue tinge. Lamps were equipped with a metal gauge to measure the height of the flame. Miners could place the safety lamp close to the ground to detect gases, such as carbon dioxide, that are denser than air and so could collect in depressions in the mine; if the mine air was oxygen-poor (asphyxiant gas), the lamp flame would be extinguished (black damp or chokedamp). A methane-air flame is extinguished at about 17% oxygen content (which will still support life), so the lamp gave an early indication of an unhealthy atmosphere, allowing the miners to get out before they died of asphyxiation.

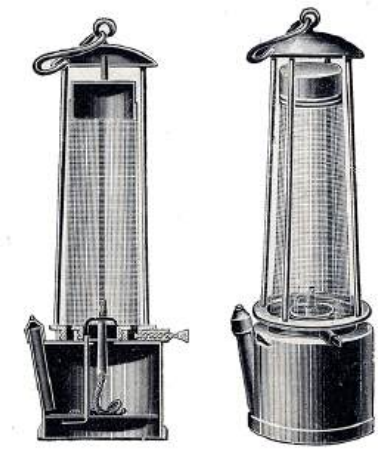

Figure 5: Miners Safety Lamp.

Excavation
The first sub-aqueous tunnel to be built was the Thames tunnel. Earlier attempts to cross the Thames had resulted in major collapses and failure. The engineer Ralph Dodd tried, but failed, to build a tunnel between Gravesend and Tilbury in 1799; in 1805–09 a group of Cornish miners, including Richard Trevithick, tried to dig a tunnel farther upriver between Rotherhithe and Wapping/Limehouse, but failed because of the difficult conditions of the ground. The Cornish miners were used to hard rock and did not modify their methods for soft clay and quicksand.

In 1814 Sir Marc Isambard Brunel proposed to Emperor Alexander I of Russia a plan to build a tunnel under the river Neva in St Petersburg. This scheme was turned down (a bridge was built instead) but Brunel continued to develop ideas for new methods of tunnelling. He developed with Thomas Cochrane and patented the tunnelling shield in January 1818. In 1823 Brunel produced a plan for a tunnel between Rotherhithe and Wapping, which would be dug using his new shield. Financing was soon found from private investors, including the Duke of Wellington, and a Thames Tunnel Company was formed in 1824, the project beginning in February 1825.

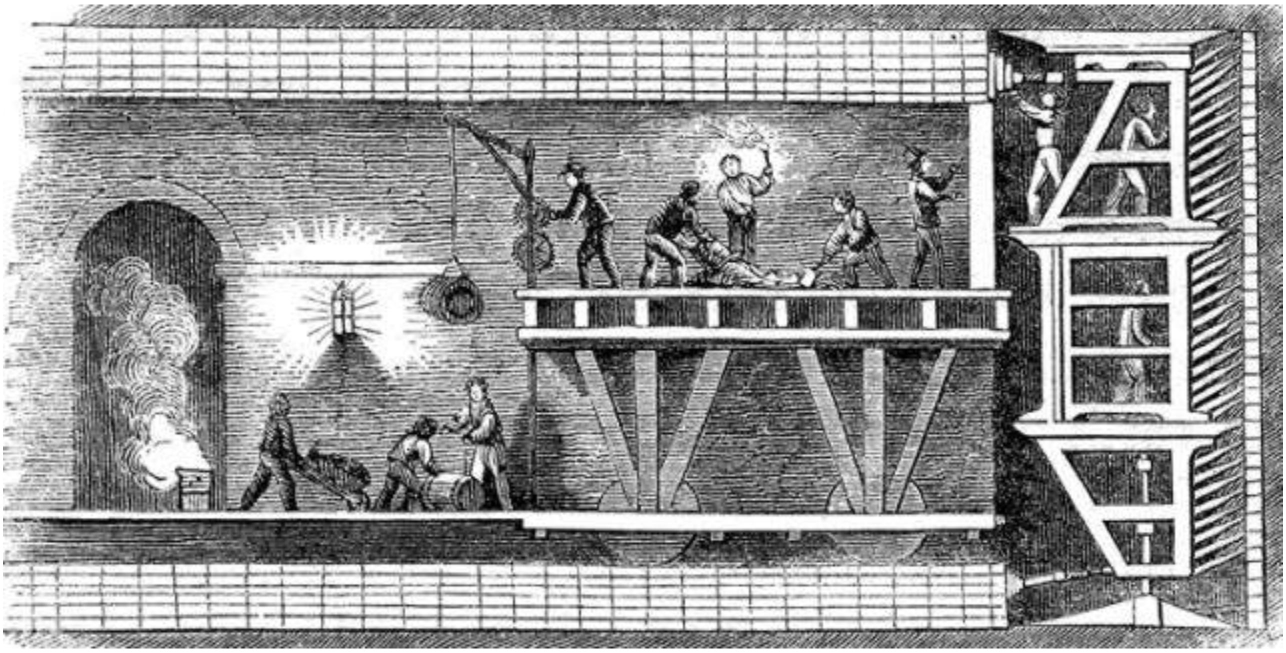

Figure 6: Brunel's tunnelling shield.

The tunnelling shield was described in the Illustrated London News in 1843:

The mode in which this great excavation was accomplished was by means of a powerful apparatus termed a shield, consisting of twelve great frames, lying close to each other like as many volumes on the shelf of a book-case, and divided into three stages or stories, thus presenting 36 chambers of cells, each for one workman, and open to the rear, but closed in the front with moveable boards. The front was placed against the earth to be removed, and the workman, having removed one board, excavated the earth behind it to the depth directed, and placed the board against the new surface exposed. The board was then in advance of the cell, and was kept in its place by props; and having thus proceeded with all the boards, each cell was advanced by two screws, one at its head and the other at its foot, which, resting against the finished brickwork and turned, impelled it forward into the vacant space. The other set of divisions then advanced. As the miners worked at one end of the cell, so the bricklayers formed at the other the top, sides and bottom.

The key innovation of the tunnelling shield was its support for the unlined ground in front and around it to reduce the risk of collapses. The tunnel flooded suddenly on 18 May 1827 after 549 feet (167 m) had been dug. Isambard Kingdom Brunel lowered a diving bell from a boat to repair the hole at the bottom of the river, throwing bags filled with clay into the breach in the tunnel's roof.

Brunel's original design was substantially improved by Peter W. Barlow in the course of the construction of the Tower Subway under the river Thames in central London in 1870. Probably the most crucial innovation of Barlow's design was that it had a circular cross-section (unlike Brunel's, which was of rectangular cross-section), which at once made it simpler in construction and better able to support the weight of the surrounding soil. The Barlow design was enlarged and further improved by James Henry Greathead for the construction of the City and South London Railway (today part of London Underground's Northern line) in 1884.

His system was also used in the driving of the tunnels for the Waterloo & City Railway which opened in 1898. The station tunnels at the City Station (now known as Bank) were the largest diameter tunnelling shields in the world at the time. To this day, most tunnelling shields are still loosely based on the Greathead shield (Gillham, 2001).

According to Hapgood (2004) the first boring machine reported to have been built was Henri-Joseph Maus's Mountain Slicer. Commissioned by the King of Sardinia in 1845 to dig the Fréjus Rail Tunnel between France and Italy through the Alps, Maus had it built in 1846 in an arms factory near Turin. It consisted of more than 100 percussion drills mounted in the front of a locomotive-sized machine, mechanically power-driven from the entrance of the tunnel. The Revolutions in Europe in 1848 affected the funding, and the tunnel was not completed until 10 years later, by using less innovative and less expensive methods such as pneumatic drills.

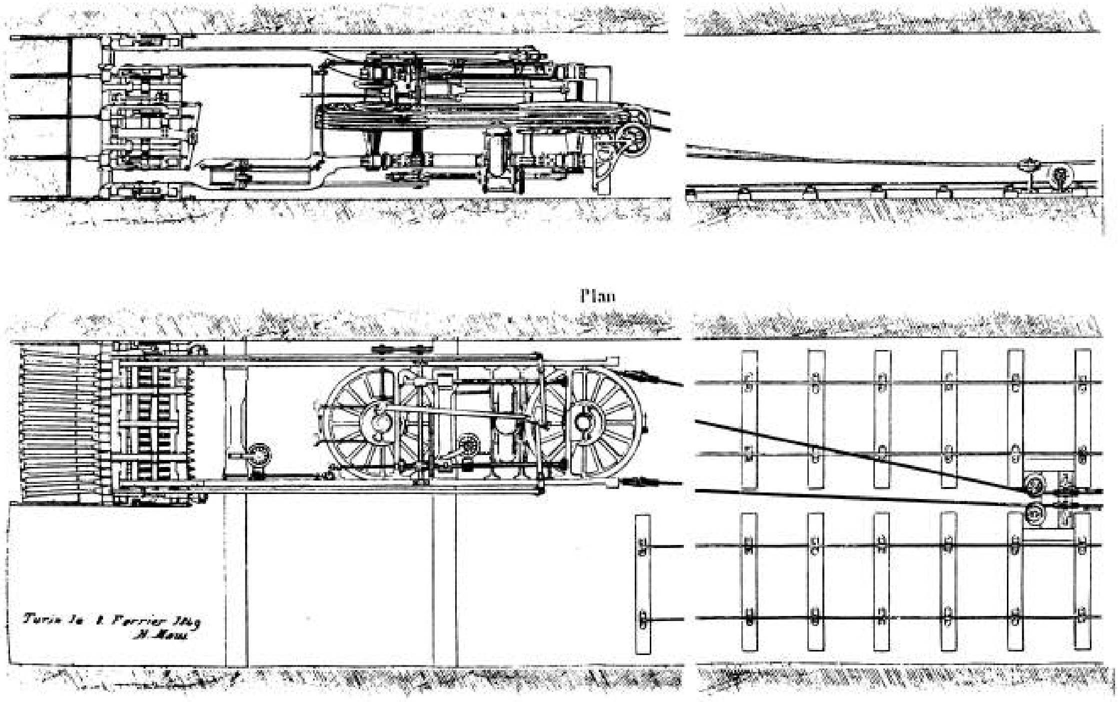

Figure 7: Tunnelling machine by H.J. Maus, Mount Cenis Tunnel 1846.

However in the United States, a boring machine was built in 1853 during the construction of the Hoosac Tunnel. Made of cast iron, it was known as Wilson's Patented Stone-Cutting Machine, after inventor Charles Wilson. It drilled 10 feet into the rock before breaking down, but Wilson's machine anticipated modern tunnel boring machines (TBMs) in the sense that it employed cutting discs, like those of a disc harrow, which were attached to the rotating head of the machine. In contrast to traditional chiselling or drilling and blasting, this innovative method of removing rock relied on simple metal wheels to apply a transient high pressure that fractured the rock.

The first TBM that tunnelled a substantial distance was invented in 1863 and improved in 1875 by British Army officer Major Frederick Edward Blackett Beaumont to excavate a tunnel under the English Channel (Gourvish 2006). The cutting head of the TBM consisted of a conical drill bit behind which were a pair of opposing arms on which were mounted cutting discs. From June 1882 to March 1883, the machine tunnelled, through chalk, a total of 6036 feet (1.84 km). However, despite this success, the cross-Channel tunnel project was abandoned in 1883 after the British military raised fears that the tunnel might be used as an invasion route. Nevertheless, in 1883, this TBM was used to bore a railway ventilation tunnel — 7 feet (2.1 m) in diameter and 6750 feet (2 km) long — between Birkenhead and Liverpool, England, through sandstone, under the River Mersey.

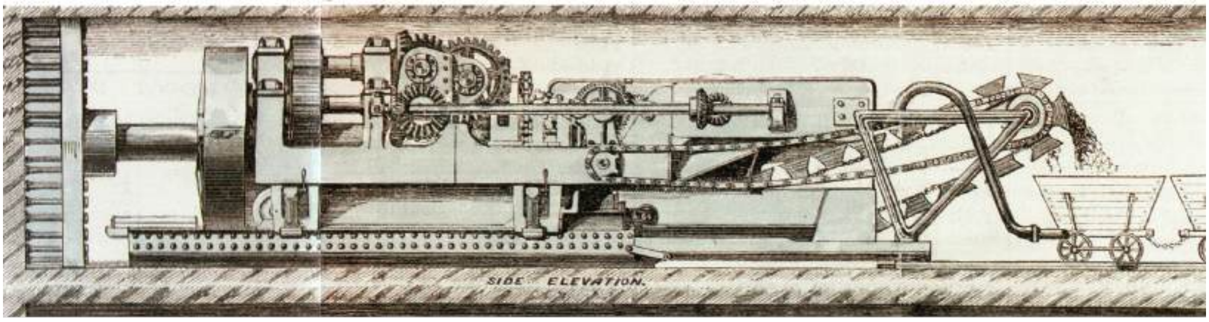

Figure 8: Beaumont's tunnel boring machine.

MODERN DEVELOPMENTS

Trackless mechanised mining
Typical mining projects around the world have been developed with rail tracks, but with the need for greater efficiency and greater economy and less rich orebodies, the application of more mechanised equipment has developed. Today multiple narrow reefs in South Africa are mined at large stoping heights with multiple boom drill rigs and large capacity loaders, which were previously excavated as single narrow stopes.

Today most drill and blast tunnels and large-scale underground mining projects utilise multi-boom hydraulic drill rigs and haulage trucks or load haul dump (LHD) machines.

Autonomous Mining Equipment
In dangerous mining situations, mining is carried out by remote controlled equipment. The modern development of robotic excavation could see the underground miner obsolete.

The mining industry, traditionally associated with high-risk labour and capital-intensive infrastructure, is increasingly turning to autonomous solutions that promise not just productivity lifts but fundamental changes to safety, business models, and sustainability. The autonomous mining equipment adoption represents a pivotal shift that may soon redraw the global mining map, as companies embrace data-driven operations to maintain competitive advantage.

The term 'autonomous mining equipment' spans several categories of operational intelligence and human oversight - namely:

Fully Autonomous: Equipment is capable of executing its tasks—hauling, drilling, or loading—without direct, real-time operator intervention. Onboard and remote AI algorithms handle decision-making, using a suite of sensors for navigation and obstacle avoidance.

Autonomous-Ready: These machines contain the hardware and control platforms for autonomy but may currently operate in manual or semi-autonomous modes due to site-specific or regulatory constraints.

Tele-Remote Operated: Multiple key mining assets are now piloted from remote stations. Here, operators control machinery using video feeds and sensor data, enabling personnel to stay away from hazardous zones.

Equipment categories include haul trucks, LHDs and surface drills. The sensor mining advancements typically include sophisticated architecture with GNSS and high-precision GPS for positioning. Furthermore, LiDAR systems enable 3D environment mapping, while proximity sensors and cameras detect personnel and obstacles. Advanced AI-enabled control units provide real-time navigation and diagnostics.

Deployment of autonomous mining equipment is typically justified by measurable, multi-dimensional gains such as:

Productivity Gains arising from perfectly-timed dispatch, consistent operation, and minimised idle times.

Operational Hours: Mines extend working hours beyond typical manual shift patterns, minimising lost time to shift handovers or worker fatigue.

Fuel and Maintenance Savings: Algorithms optimise routes, speed, and loading, while predictive maintenance foresees component failures before costly breakdowns.

Workforce Safety: Lowered exposure to accident risks, dust, and extreme temperatures leads to drops in recordable injury rates.

Blasting
The year 1955 marked the beginning of the most revolutionary change in the explosives industry since the invention of dynamite, with the development of ammonium nitrate–fuel oil mixtures and ammonium nitrate-base water gels, which together now account for at least 70% of the high explosives consumption.

In recent years the trend for high volume blasting trackless vehicles delivering pumpable emulsion has been developed, this is now used extensively in mining where it can be deployed at multiple faces. The system was first used in civil construction for the Sydney LPG cavern between 1997 and 2000 (Rogers, 1999).

Figure 9: ORICA bulk emulsion pump.

Tunnel boring
In the beginning of the 20th century tunnel boring machines were developed in the mines for cutting relatively soft rock such as potash. The first version from 1916 to 1917 was called the Eiserner Bergmann and had a rotating roller fitted with steel cutters as a cutting wheel, which on account of its dimensions produced rectangular sections. However, the next generation of gallery cutting machines built by Schmidt, Kranz & Co from 1931 were more successful. The three-armed cutting wheel was fitted with

needles and achieved on average 5 m per shift in Hungarian brown coal and was very similar to the TBM built by Whittaker for the Channel Tunnel in the 1920s (Stack, 2001).

The breakthrough to the development of today's TBMs did not occur until the 1950s when the first open gripper TBM with disc cutters was developed by the mining engineer James Robbins. Using this TBM in the Humber sewer tunnel in Toronto advances of up to 30 m per day were achieved in sandstone, limestone and clay.

Further American manufacturers then began building TBMs; after a short delay TBM development was also taken up in Europe but this was firstly with rotating milling wheels on which the modern roadheaders are based. In the 1960s German manufacturers began building machines similar to the American type. At the end of the 1960s inclined headings were developed using the reaming method on which modern raise bores are based.

Encouraged by the success of a 11.17 diameter TBM at the Managal dam in 1963 a 10.65 diameter TBM was used for the construction of the Heitersberg tunnel in Switzerland in 1971. This construction included the installation of rockbolts and mesh.

The first use of a double shield TBM was in 1972 with the installation of a segmental lining behind the cutter head and this was developed further for the Channel Tunnel excavation in the 1980s.

Until 1983 mainly hydroshields were used in soft ground based on the Wayss & Freytag patent with an air-cushion and bentonite supported face. Earth pressure balance (EPB) machines were developed based on the Archimedes screw and maintaining enough broken material at the face to provide face support. In the 1990s the emphasis was on mix-shields, TBMs able to deal with both hard rock and soft ground (Herrenknecht, 1996).

In August 2014, a Robbins Dual Mode EPB/Rock TBM was successfully rolled out from the first of two access tunnels at Grosvenor mine in Queensland. The specialised machine is the first TBM to be used at a coal mine in Queensland, and there are many aspects of both the TBM and project that make it unique. The ground conditions consist of sedimentary hard rock up to 120 MPa UCS, and mixed ground of mainly sand and clay, and coal seams. The 8.0 m (26.2 ft) Robbins machine and continuous conveyor system were chosen over the traditional roadheader method for several reasons, including speed of excavation—the swift machine has proven to be about ten times faster than a roadheader and mine life — with these tunnels needing to remain intact for the life of the Grosvenor mine [about 40 years], and be maintenance-free with cement linings.

Figure 10: A Robbins Dual Mode EPB/Rock TBM Grosvenor Decline Tunnel Project in Queensland, Australia.

Rock support
Shotcrete and rock bolts have become the norm in underground support. The first development of shotcrete for support – previously called gunite or pneumatically applied mortar – was invented in 1907 by American taxidermist Carl Akeley to repair the crumbling facade of the Field Columbian Museum in Chicago. It was first used underground to fire-proof mine drifts in the 1920s. World War II developments saw new types of 'continuous feed' systems that could deliver and project shotcrete in a continual stream, but a further breakthrough was made in 1955, when the 'wet-mix' process was introduced, which saw components mixed with water before entering the hose rather than upon delivery via the nozzle.

The first major application for underground support was in the late 1950s for the Snowy Mountain Hydro-electric Scheme. This hydro-electric scheme is considered one of the engineering wonders of the world with over 126 km of tunnels, eight dams, five power stations (three of which are underground).

At this time rock bolting was also not recognised as a standard system of rock reinforcement with most civil tunnels concrete lined throughout and mining tunnels relying on timber and steel sets. The Snowy mountains hydro electric project pioneered the use of shotcrete and rock bolts with many kilometres of tunnel remaining 'unlined'. Extensive laboratory modelling was carried out (Alexander and Hosking, 1971). Laing, (1961) developed a set of design rules for pattern rock bolting that related rock bolt length and spacing to block size. The rock engineering expertise developed in the Snowy Mountains Hydro-electric scheme was soon transferred into the Australian mining industry and elsewhere around the world (Hoek & Brown, 1980).

Shotcrete became an integral part of the New Austrian Tunnelling Method in the 1960s (Rabcewiz, 1964) by which excavation is controlled by continuous monitoring of ground movements.

The introduction of steel fibres in 1971 and its application by the Norwegian tunnelling industry in the late 1970s has also had a major impact on mining. Initially shotcrete was applied with layers of mesh which were both time-consuming and cumbersome.

Today more than 800,000 m3 of shotcrete is sprayed in Australia annually with 70% underground. Shotcrete application is now a huge global industry expected to be worth more than $10 billion.

Figure 11: Shotcrete application Cadia East mine, NSW Australia.

The Cadia East Project is delivering what will become the largest underground mine in Australia and one of the largest underground gold mines in the world; fibre-reinforced shotcrete has been essential for the safe development of this world-class project. Cadia East has an approved mine life of 21 years and is forecast to increase the company's annual production of 700,000 to 800,000 oz (20,000 to 23,000 kg) of gold and 99,000 tons (90,000 tonnes) of copper in the coming years. The massive underground gold and copper resource at Cadia East is suited to the low-cost, bulk underground mining method known as panel caving. Panel caving is a natural caving method which uses ground stresses, rock structures, and gravity to break the rock and propagate mining vertically. The Cadia East Project commenced the main shotcreting segment of the underground development in June 2010 and had excavated over 40 miles of tunnels. All development is excavated using drill and blast with a fleet of four boring jumbo drill rigs backed up by 10 rock bolting jumbos. Every tunnel and chamber has been supported with fibre-reinforced shotcrete, with a total of 150,000 yd3 (115,000 m3) sprayed as of November 2013. The shotcrete is all supplied as fibre-reinforced wet mix and applied in-cycle before rock bolting. At the peak of project development, five to six Jacon Roboshot Maxijet spray rigs were used at any one time with a fleet of four boring jumbo drill rigs backed up by 10 rock bolting jumbos (Duffield, 2014).

Grouting and ground treatment

The first recorded application of grout injection to stabilise civil structures is by Charles Berigny (Glossop, 1961) in 1802 for the Port of Dieppe in France; he went on to develop various injection processes in soft ground following the patenting of Portland Cement in 1824. However, the first recorded example of using cement to seal off water ingress in mining was in Germany in 1864 (Bachy, 1934) when a brick lined tunnel near Hamburg was sealed by "running in milk of cement from the surface by means of a hand pump". In the same year Barlow is accredited of inventing a method of injecting a lime slurry behind cast iron tunnel linings and Greathead is noted as using a hand syringe to grout the annulus of the Tower Subway Tunnel in London clay beneath the river Thames in 1869 (Tirdo, 1994). However the work was not entirely satisfactory as "the pressure that could be applied by the syringe was not sufficient to force it (the grout) properly home into the spaces to be filled". The first recorded use of cement grouting in a rock tunnel was in 1880 at Maret in France (Bradt, 1909).

At the turn of the century cement grouting was used extensively as a remedial measure to deal with water ingress in the coalfields of France, Belgium and Germany and mines in the USA and the use of grouting as a massive seal for tunnels associated with dams was reported in the USA by Sanbarn and Zipsun in 1920, including tunnels beneath the Hudson and Harlem rivers.

In 1933 Maurice Lugeon published borehole watertightness criteria which is still the basis of our grouting definitions today (Glossop, 1962). With the invention of the strain viscometer and the Marsh cone in 1931 engineers were able to better determine the flow characteristics of grouts to permeate fracture in rocks or soil pores (Terzaghi, 1935). Australian guru Houlsby (1972) greatly improved the interpretation of the multi-pressure Lugeon tests.

The invention of the colloidal mixer by J.P. Morgan in 1934 and manufactured by Colcrete in England from 1937 was a major result for grouting. Its high-speed high-shear action removed air from the cement, improved wetting and increased the proportion of fine cement particles, resulting in a grout that required less dilution with reduced segregation, lower bleed and higher strength (Tirdo, 1994).

Silicate and chemical grouts were introduced by Lemaire and Dumont and others at the turn of the 19th century with the introduction of dilute silicate and acid solution into firmer ground sandstones. This was then developed further by a Dutch engineer Hugo Joosten (Karol,1983). Developments of sodium silicate grouting in the 1950s included Soletanche's hard silicate gel (Tirdo, 1994). However in 1957 Kell reported the first use in the UK tunnelling industry of clay/cement and clay/chemical grouts for compressed air tunnelling under the river Thames at Dartford (Trench& Hillman, 1984). In the same year the Ashe published state-of-the-art data on chemical grouting (Joosten, 1954). By the 1960s grouting of alluvium was accepted worldwide and included construction of the new Blackwall Tunnel in London and the Whiteinch Tunnel near Glasgow (Glossop, 1960). By mid-1960 the grouting limits for common grout mixes were well appreciated. In the 1970s concern over health and environmental pollution led to a ban on many chemical grouts, particularly in Japan. CIRA produced guidelines on the safe use of chemical grouts in the UK in 1981.

Jet grouting emerged as an alternative to chemical grouting in the 1970s with major application for the Singapore Metro in the 1980s and application for shaft sinking at Cannington mine.

Singapore began building its Mass Rapid Transit system in the 1980s. One of the first sections was along the busy shopping centre of Orchard Road. Orchard Road is a 2.2 km-long street that is the retail and entertainment hub of Singapore. It is a major tourist attraction, in addition to being the most popular shopping enclave in the city. Concern over high-rise buildings' settlement along Orchard Road from the tunnel construction prompted the use of jet grouting as an umbrella above the tunnel to limit ground settlement.

The Cannington deposit was discovered in the June 1990 development of the underground mine which began in 1996. The two shafts were needed to go through a soft saturated sandy layer extending from 60 to 80 m depth to reach final shaft depths of 600 m and 400 m respectively. In a world first in December 1996 GFWA conducted high pressure jet grout mixing to depths of 80 m at the mine site.

The final construction of the hoisting shaft consisting of a total of six grouted columns of 4 x 1.6 m and 2 x 1.4 m diameter extending from 65 to 86 m in depth, with the ventilation shaft consisting of four grouted columns 2.0 m in diameter extending from 56 to 64 m in depth. The total volume of soil treated was 392 m3 and the total amount of cement used was approximately 285 t.

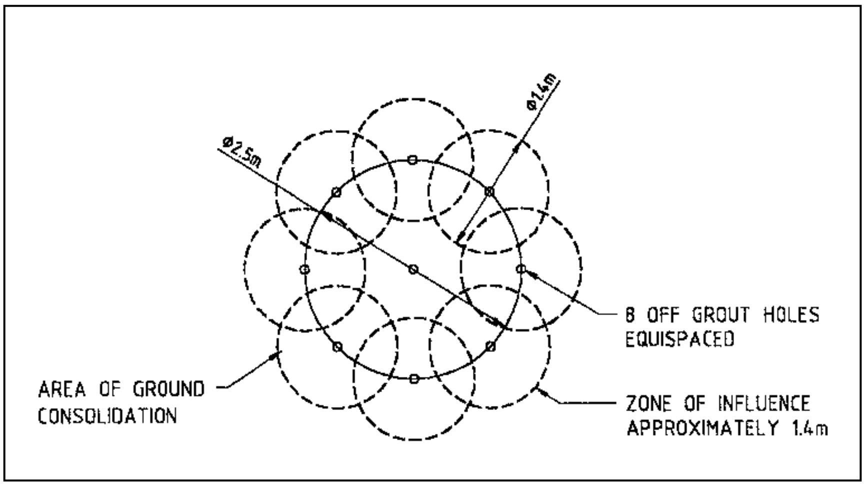

Figure 12: Jet grouting layout at Cannington Mine, Queensland, Australia.

The introduction in the 1980s and in 1989 the success of microfine cements was recorded in material with otherwise poor penetration.

In 2002, Garshol outlined the advances in cement-based grout materials technology, equipment and practical procedures that have taken place over the past 15 years. These developments, including the use of stable non-bleed micro-cement-based grouts with adjustable setting time, are now offering major advantages over more traditional cementitious grouting practices. Roald writes that modern grouting technology has now developed to such an extent that grouting should be considered as a third principal tunnelling process alongside excavation and rock support (Roald *et al.,* 2002).

Today, pre-injection grouting using advanced cementitious grouts, sometimes supplemented by various forms of chemical grouts, performed from within the tunnel, ahead of tunnel advance has become a very important and widely practised (though not widely understood) activity for the purposes of groundwater control and to improve ground stability, particularly in rock tunnels.

CONCLUSION

So, what has the mining industry done for civil underground construction and what has civil underground tunnelling done for mining? The answer is much.

The development of techniques used today in underground construction has benefitted from both mining and civil applications.

There is still more underground excavation carried out in the world in mining than in civil engineering. The deepest mine in the world is TauTona in Carletonville, South Africa or Western Deeps No 3 shaft at 4 km deep. The largest underground mine is Kiirunavaara mine in Kiruna, Sweden with 450 km of roads, 40 million tonnes of ore produced yearly, and a depth of 1270 m, it is also one of the most modern underground mines.

But civil engineering structures are more complex and are typically in more restrictive urban settings requiring longer design life. The Gothard Base Tunnel in Switzerland with a route length of 57.09 km and a total of 151.84 km of tunnels, shafts and passages, is the world's longest and deepest traffic tunnel with a maximum overburden of 2300 m.

The longest underwater tunnel in the world is the Seikan Tunnel which is a 53.85 km dual gauge railway tunnel in Japan, but has only a 23.3 km long portion under the seabed. The track level is about 100 m below the seabed and 240 m below sea level. However the 50.5-km Channel Tunnel between the United Kingdom and France has a longer undersea portion of 37.9 km and at its lowest point it is 75 m deep. China is moving forward with one of the world's most ambitious infrastructure projects: a 120 km undersea tunnel across the Bohai Strait. About 90 km of the 120 km tunnel will run underwater, making it the world's longest sub-sea tunnel.

Mining engineers will continue to find opportunities in underground civil engineering projects and developments from civil engineering underground construction will continue to find application in underground mining. The two industries are interrelated, and we must continue to work together.

REFERENCES

Alexander L.G., and Hosking A.D., (1971) *Principles of rock bolting – formation of a support medium.* Proc. Symp. Rock bolting. Illawarra Branch AusIMM. February 1971 1.1-1.21

Bachy P. (1934) *Materials et methods d'injection dans les travaux publics.* Science et Industry 4 154 – 160.

Boon, G. C. and Williams, C. (1966) *The Dolaucothi Drainage Wheel*. Journal of Roman Studies, 56, 122-127.

Bradt. E.F. (1909) *Crevices in Salt Shaft.* Mining World Vol 30 (12) 20th March 1909.

Glossop. R., (1962) *Symposium on Grouts and Drilling Muds in Engineering Practice – Opening Address*. Butterworth, London.

Chadwick, J. (2012) *Trackless tramming*. International Mining. June 7 2012

CIRIA (1982) *Health and Safety Aspects of Ground Treatment Materials*. Report No 95. London

Cressy, D. (2013) *Saltpeter: The Mother of Gunpowder*. Oxford University Press

Duffield, S. (2014) *Shotcrete application at Cadia East Project.* ATS Journal. Paragon Press. October 2014

Gillham, J.C. (2001) *The Waterloo & City Railway*. The Oakwood Press, Usk

Garshol K. (2002) *Modern Grouting Techniques.* Water Control in

Glossop. R., (1961) *The Invention and Development of Injection Processes - Part II 1850-1860*. Geotechnique 11. 225-274

Gourvish, T. (2006) *The Official History of Britain and the Channel Tunnel.* Abington, England: Routledge, Chapter 1, § 2:

Hapgood, F (2004) *The Underground Cutting Edge: The innovators who made digging tunnels high-tech.* Invention & Technology Vol.20, #2

Herrenknecht, M. (1996) *Latest development in mechanised tunnelling technology.* Tunnel Boring Machines – Trends in Design & Construction of Mechanised Tunnelling. Ed. Wagner and Schulter. Balkema, Rotterdam 1996 pp 55-60

Hoek, E. and Brown, E.T. (1980) *Underground Excavations in Rock*. Institute of Mining and Metallurgy. London

Holland, J (1841). *The History and Description of Fossil Fuel, the Collieries, and Coal Trade of Great Britain*. London: Whittaker and Co (Digital edition Kress Library of Business and Economics, Harvard University). pp. 267–8.

Houlsby. A.C., (1972) *Construction and Design of Cement Grouting*. John Wiley and Sons New York.

Joosten A.J. (1954) *The Joosten Process for Chemical Soil Solidification and Sealing and it's Development from1925 to Date*. N.V. Amsterdansche Ballast, Mjaatschappj.

Karol R.H. (1983) *Chemical Grouting* Marcel Dekker, New York.

Lang, T.A. (1961) *Theory and practice of rock bolting*. Tans. Soc. Min.Eng. AIME 220: 330-348

Lees, D. (2004) *The history of drill and blast.* AUCTA Tunnelling Course. UNSW, Sydney 2001

Littlejohn S., (2003) *The Development of Practice in Permeation and Compensation Grouting*. Proceedings of 3rd International Conference on Grouting and Ground Treatment. ASCE, New Orleans , February 2003.

Pinkowski, J. (2015) *Massive Underground City Found in Cappadocia Region of Turkey*. National Geographic

Rabcewiz, L. (1964) *The New Austrian Tunnelling Method.* Water Power 16:453-457

Roald S, Barton N and Nomeland T. (2002) *Grouting – the Third Leg ofUnderground Construction.* Water Control in Norwegian Tunnelling. Publication No.12, Norwegian Tunnelling Society

Rogers S (1999) *Bulk Emulsion Explosives at the Sydney LPG Cavern — A First in Australian Tunnelling*. 10th Australian Tunnelling Conference. AusIMM. March 1999

Russell, M., (2000) *Flint Mines in Neolithic Britain*. Tempus. Stroud

Stack B., (2001) *Encyclopedia of tunnelling, mining and drilling equipment*. Muden Publishing Company. Hobart, Tasmania

Tirdo V (1994) *Shield and Compressed air Tunnelling in the 19th Century*. One hundred and twenty years of tunneling in New York City. American Society of Civil Engineering.

Terzaghi. K., (1935) *Proceedings International Conference and Soil Mechanics – Opening Discussion.* Proc. Int. Conference on Soil Mechanics 3, University of Harvard.

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David Lees and Associates

Beginning as a mining engineer in the South African mining industry in gold and platinum mines. He wrote his MSc thesis at Wits University and was involved in the introduction of trackless mining at HJ Joel Mine.

Returning to the UK in 1988 he commenced a new career in civil engineering with piling works at Canary Wharf, design for Jubilee Line Extension and CrossRail and cavern excavation in Jersey. Emigrating to Australia in 1995 he was supervising engineer at the Sydney LPG Cavern and Technical Advisor for the New Southern Railway as well as inspection of Snowy Hydro tunnels

David Lees and Associates was established in 1999 providing consultancy to civil and mining projects across Australia and Asia including Lane Cove Tunnel, Parramatta Rail Link, Delhi Metro, Singapore Deep Sewer System, Narrows Crossing LNG tunnel, inspection of Sydney sewer tunnels, grouting consultant for Blakefield South Colliery, plug designs for Russel Vale Colliery, and provided grouting and drainage proposals to Newcrest Mining for Havieron Decline.

Appointed as National Tunnel Manager for KBR in June 2002 and Manager of the NSW Civil Group, he was Banks Engineer for Lane Cove Tunnel and Brisbane By-pass, Technical Advisor for Metro West, and security advisor for Cross City Tunnel, carried out an inspection of the Otira Tunnel in New Zealand and a safety audit of a gold mine in Western Australia.

David established Grouting and Foundation Works Australia in June 2004 which provided specialist grouting and waterproofing for building, civil and mining projects across Australia including Shannon Creek Dam, Ranger Mine, Cross City Tunnel, and Pelican Point Power Station.

In July 2014 David was appointed as Senior Tunnelling Engineer for the Melamchi Water Supply Project in Nepal where he worked throughout the earthquakes of 2015. In August 2015 he was appointed as Chief Site Supervisor for the Uma Oya Project.

He returned to Australia in 20018 assisting in finalising the Snowy 2 contract documents, and as Principal Tunnelling Engineer with Jacobs he was CPS Manager at WestConnex, technical reviewer for Brisbane Metro, Baroota Pumped Hydro, More Trains More Services for Tansport NSW, Aukland Central Interceptor and Batang Toru Hydro Project in Sumatra.

Appointed Team Leader for Package 7A and 7B by AECOM of the Rishikesh-Karanprayag railway tunnels in Utarakhand in Northern India in September 2020, and Chief Resident Engineer for the Mahawelli Water Security Investment Program in Sri Lanka in 2021

David is currently Project Manager and Team Leader for the Tanahu Hydropower Project in Nepal.

David is a Fellow of the Institute of Engineers Australia, He was a Director of Engineers Media and has been Editor of the Australian Tunnelling Society Journal for 27 years. He has published two history books on tunnelling and three engineering novels.